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May, 1956

Volume 68 Number 2

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The feather-lightness and miniature size of the transceiver and receiver make it possible, for the first time, to extend communication to the individual level. It is another instance of RCA's constant search for new and better ways of doing things electronically. Demonstration and consultation with RCA field engineers throughout the world are invited. Call or write.

RCA Ultra-Miniature FM Transceiver compared with AN/PRC-10 (Walkie-Talkie)

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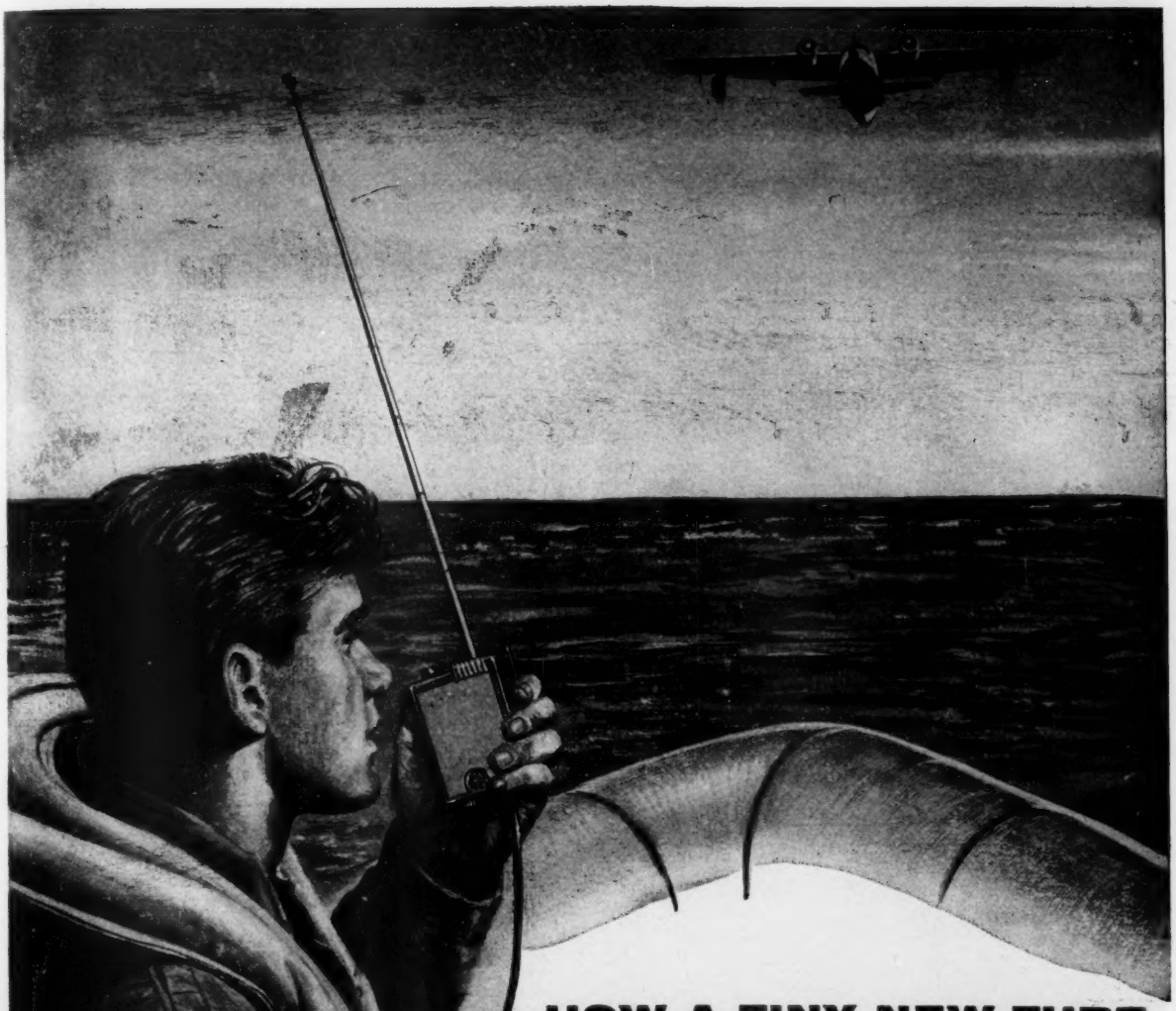

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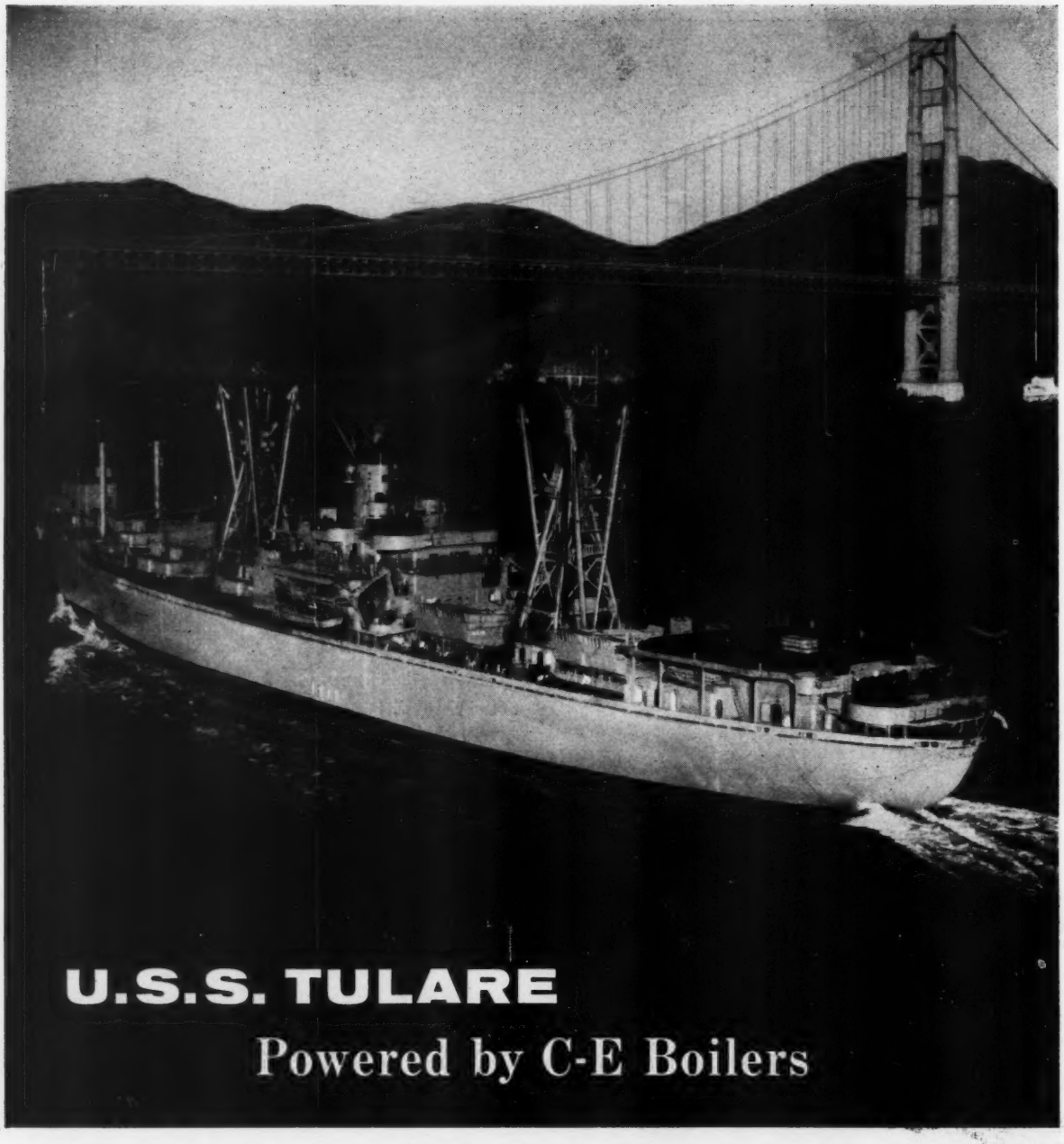


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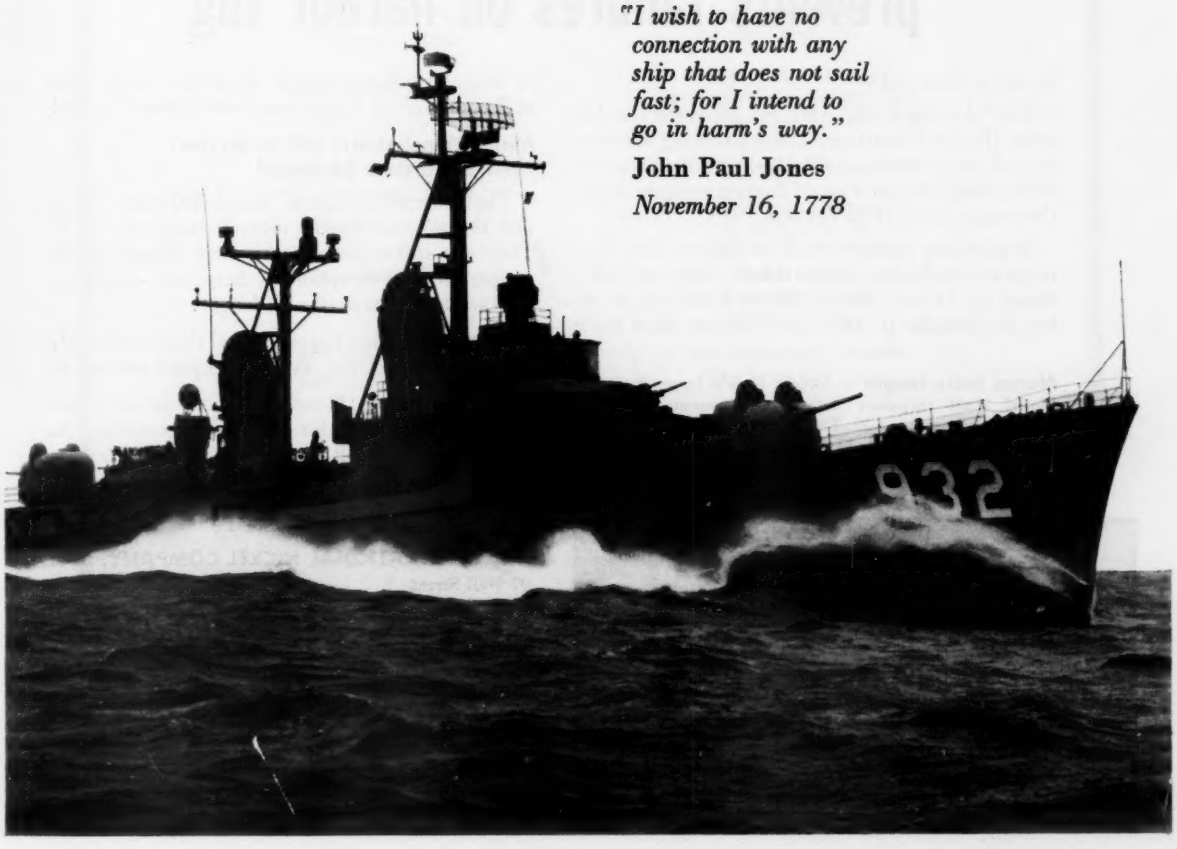
*November 16, 1778*



***ANGELS GATE*** — When her steel shaft failed, Los Angeles Harbor Department engineers specified a Monel replacement.

## *Replaces steel:*

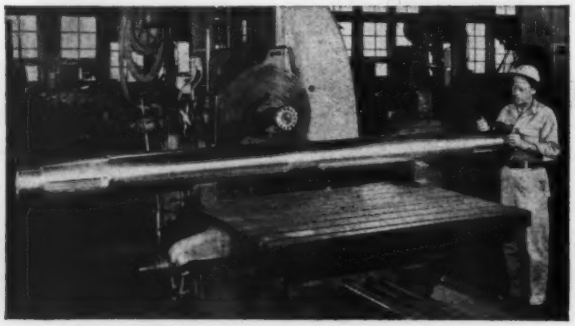
# World's largest diameter Monel shaft prevents failures on harbor tug

It was a close call —

The "ANGELS GATE" (tug No. 10 of the Los Angeles Harbor Department) was handling a heavy-derrick barge when — suddenly — her steel propeller shaft failed. Only luck saved floating equipment and the nearby dock from damage.

Department engineers took no chances when they replaced this broken steel tailshaft. They ordered a 9-inch by 11-foot shaft of Monel nickel-copper alloy. In diameter it's the world's largest shaft made of this alloy. But in length of service, it will face stiff competition. From many *other* Monel shafts!

***Monel lasts longer*** — Angels Gate's large diameter Monel shaft surpasses A.B.S. requirements for steel shafts in a boat her size. The keyway is filleted for even greater strength at Todd Shipyards, San Pedro, Calif. Note how the shaft has been machined to save the cost of wearing sleeves.



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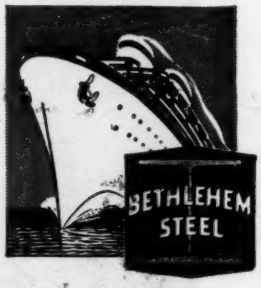


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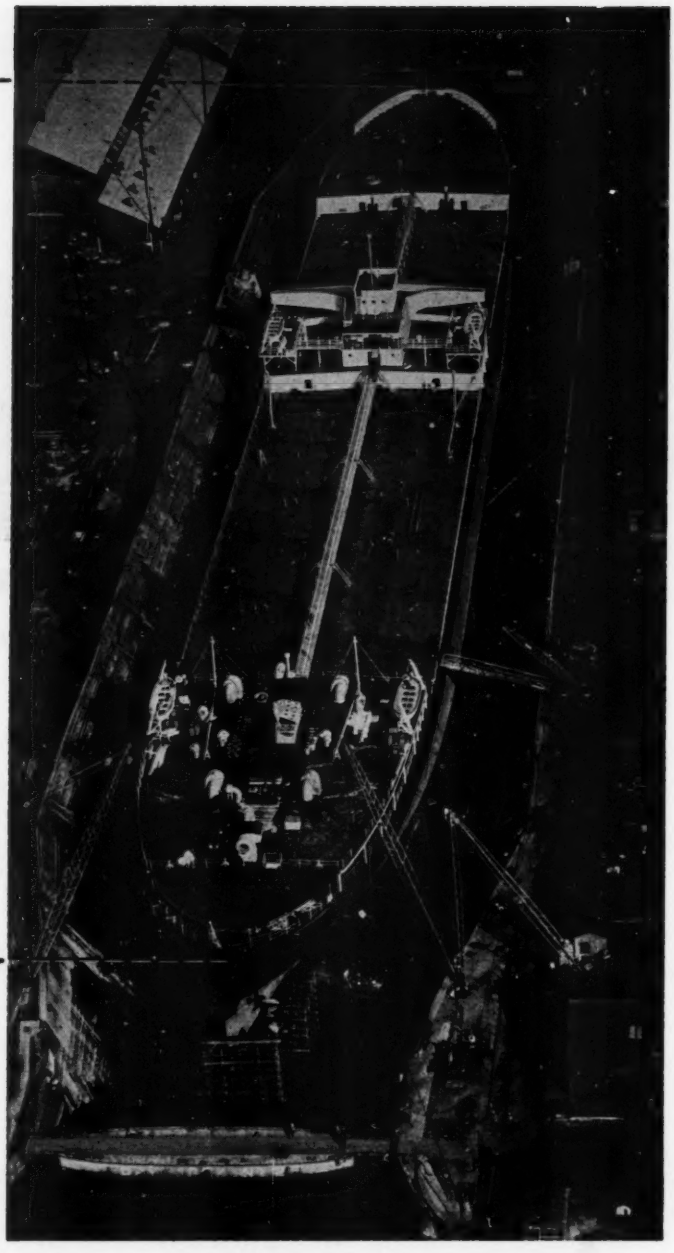
## ...but no problem to this graving dock



The tanker Petrokure, shown in Newport News' 800-foot graving dock for voyage repairs, is owned and operated by Universe Tankships, Inc. She has the greatest beam of any vessel ever docked in this facility. The Petrokure... a vessel of 21,262 gross tons... has the following dimensions:
Length overall .....673′ Beam .....92′ 2″

The trend toward larger tankers can bring on problems when overhauls are needed...

However, this 800-foot graving dock... a typical example of the many Newport News facilities for repairing ships... handled even this large tanker.

Here at Newport News, you will find not only ample space in a completely equipped plant, but also the particular engineering talents along with the skill and facilities that best suit your needs.

Together they help cut costly lay-up time, whatever the vessel's size. Newport News thus plays an important role in aiding ship owners and operators to keep cargo moving.

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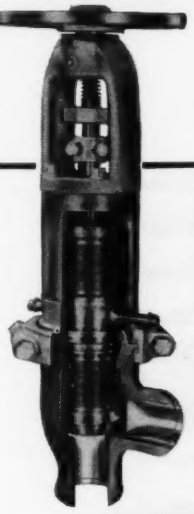

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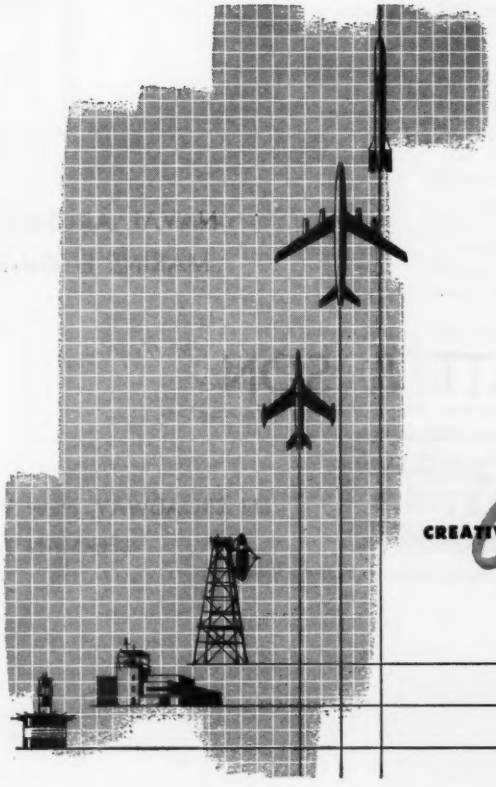

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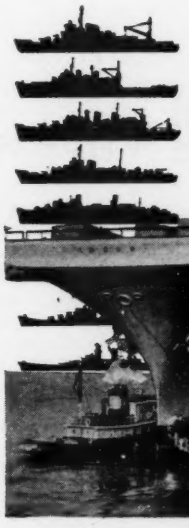
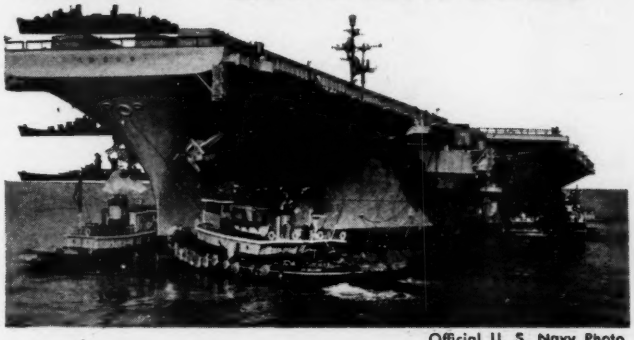
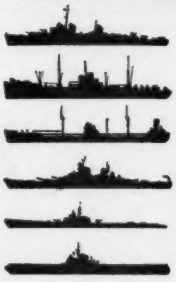


# Freedom's family has a new sister



Official U. S. Navy Photo



Her name is *Saratoga.* There's nothing new about the name and there's nothing new about what that name stands for. Her reason for being is as old as the history of free men.

She's the most formidable fighting ship ever built and she exists for the same pure reasons as the Magna Charta or The Bill of Rights.

The U.S.S. *Saratoga,* like the U.S.S. *Forrestal,* is here because she *has* to be—the need for her and others like her has never been more obvious. And free men everywhere know that the most subtle reminder that freedom is here to stay is, very often, the most obvious.

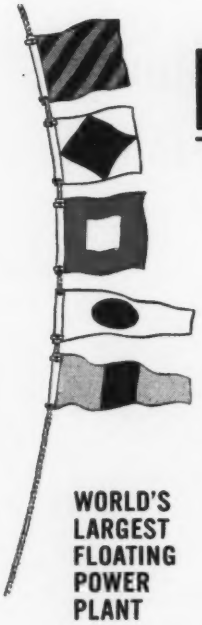
*The Babcock & Wilcox Company, whose boilers supply power to the U.S.S. Saratoga, the U.S.S. Forrestal, and so many thousands of other American ships, is continuing to work in the tradition of engineering excellence which has made the U. S. A. the world's leader in the design and construction of merchant and naval vessels.*

BABCOCK & WILCOX

BOILER DIVISION

M-588

THE BABCOCK & WILCOX COMPANY, BOILER DIVISION, 161 East 42nd Street, New York 17, N. Y.



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# FW-powered for overall economy

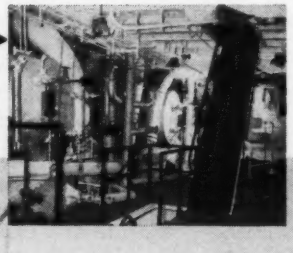
The world's largest floating power plant, the YFP-10 can supply the electric service needs of all but the largest port cities, industrial plants and Navy Yards. Permanently moored, it may be employed as a main source of power—or as a supplementary source where existing facilities are overtaxed. It can also serve in times of natural disaster, enemy bombing or other emergencies.

Designed to equal or exceed the efficiency of a shore-built plant of equal output, the YFP-10 can go from a "cold ship" to full power output in four hours. Operation at normal load can be continued for 30 days without refueling.

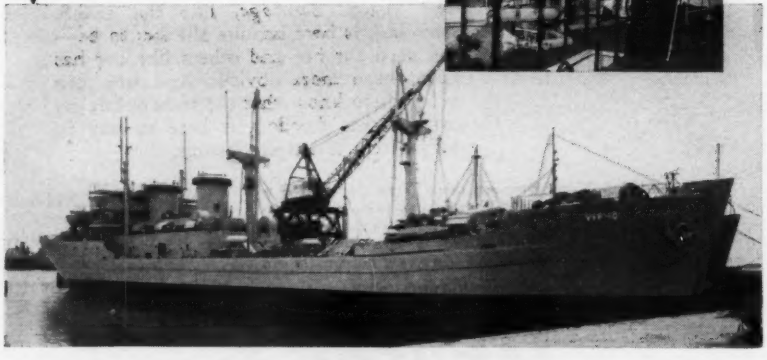
To promote overall economy, three top-fired Type-D Foster Wheeler steam generators of advance design have been installed. These units are capable of delivering 123,000 lbs per hr at 600 psig, 825F, and are complete with Foster Wheeler superheaters, economizers and air heaters. *Foster Wheeler Corporation, 165 Broadway, New York 6, N. Y.*

**WORLD'S LARGEST FLOATING POWER PLANT**

View showing top-fired Type-D Foster Wheeler steam generators. ▶



U. S. Navy YFP-10, turbo-electric generating plant, capable of delivering 34,000 kw at 13,000 v. Built for the Bureau of Yards and Docks by the Gibbs Corporation, Jacksonville, Fla. Power plant designed by Reynolds, Smith and Hills, Engineers, Jacksonville, Fla. ▼



FOSTER WHEELER

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**Technical Assistance.** The American Brass Company's metallurgical engineers and its sales representatives throughout the country are available to help you in the selection of the ANACONDA Condenser Tubes to meet your problems. Write: Technical Department, The American Brass Company, Waterbury 20, Conn. In Canada: Anaconda American Brass Ltd., New Toronto, Ont.

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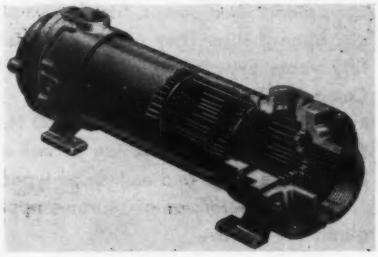

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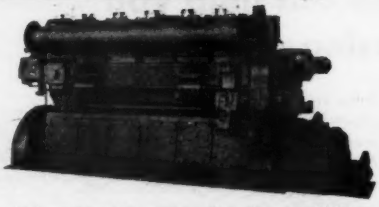

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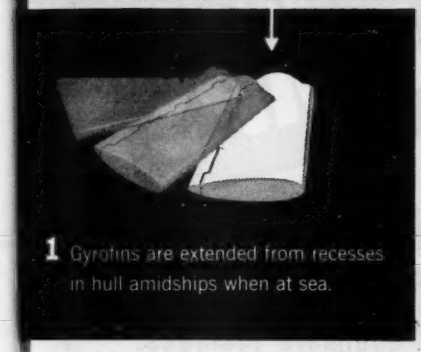
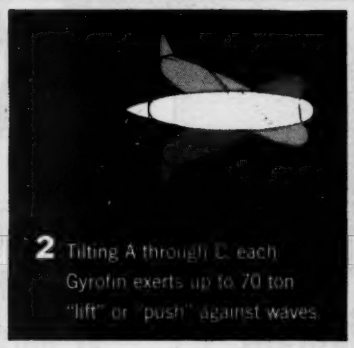


1 Gyrofins are extended from recesses in hull amidships when at sea.



2 Tilting A through C, each Gyrofin exerts up to 70 ton "lift" or "push" against waves.

3 RESULT: Stabilized ship improves course and speed while unstabilized ship is forced to cut speed.

# SPERRY ANNOUNCES STABILIZER FOR NEW AND EXISTING SHIPS

## Folding Fin Design Conserves Space and Simplifies Installation

### THE STORY BEHIND THE STORY:

Whether you're interested in carrying passengers or cargo—or both—the new Sperry Gyrofin* Ship Stabilizer offers you many advantages and operating economies. With the Sperry Gyrofin, you can "sell" passenger comfort throughout every season of the year. With it, you can reduce ship damage in heavy seas and eliminate shifting cargoes—especially important when perishables are being carried. And, most important to operating economy, you can improve course and speed in heavy weather thus saving fuel and time between ports. In bringing this development to the maritime trade, Sperry engaged the hydrodynamic experience and shipbuilding facilities of the Newport News Shipbuilding and Dry Dock Company.

**REDUCES SHIP ROLL UP TO 90%**

■ Effectiveness of the Sperry Gyrofin, illustrated above, is due to the control system which automatically senses and measures the roll *rate*, the roll *angle* and the roll *acceleration*. Through these signals, the hydrofoil-type fins are constantly positioned to exert anti-roll forces of precision magnitude and timing. Each of two underwater fins can exert up to 3000 foot-tons of "lift" or anti-rolling moment within two seconds.

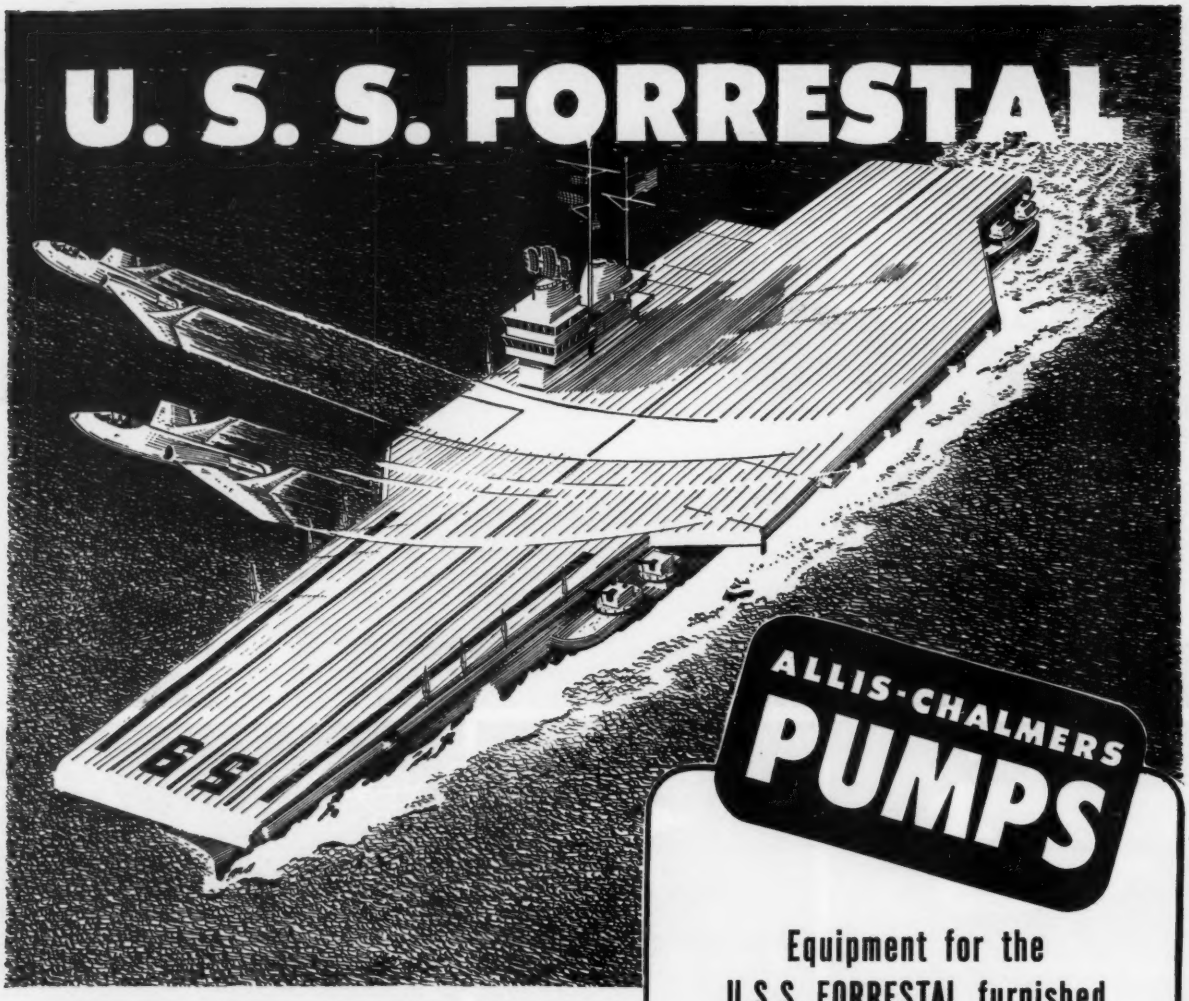
**REQUIRES LITTLE SPACE**

■ Because of its folding design within fin boxes, the Sperry Gyrofin is readily installed in the hull of the ship with a minimum of interference to cargo space. The entire installation with hydraulic gear takes up only a small portion of a single compartment of a ship. When not in use the fins feather and fold back into the fin boxes.

■ Our Marine Division will be happy to discuss Gyrofin installations with you—whether for existing ships or those under construction.

SPERRY GYROSCOPE COMPANY
Great Neck, New York
DIVISION OF SPERRY RAND CORPORATION

# U. S. S. FORRESTAL



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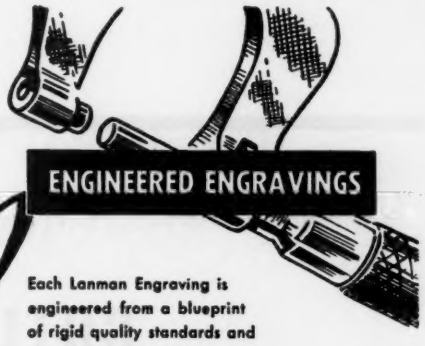


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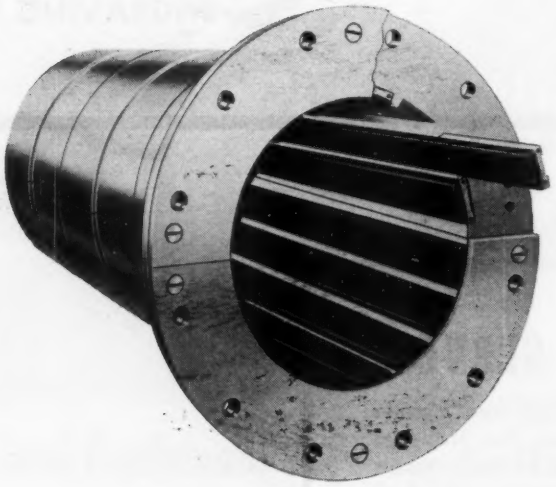
for

Stern Tubes and Struts



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## DE LAVAL *main propulsion unit powers the S S Golden Bear*

The SS GOLDEN BEAR is the first of three specially modified Mariner type vessels for Pacific Far East Line. A De Laval main propulsion unit, delivering 19,250 shp, propels this vessel. Two other sister ships, the Korean Bear and Japan Bear will also be powered by identical De Laval equipment.

*For years, fleet operators have looked to De Laval for dependable, precision-made marine equipment to power passenger and cargo ships, tankers, ore carriers and many other types of vessels.*

DE LAVAL *Marine Division*

DE LAVAL STEAM TURBINE COMPANY

*Trenton 2, New Jersey*

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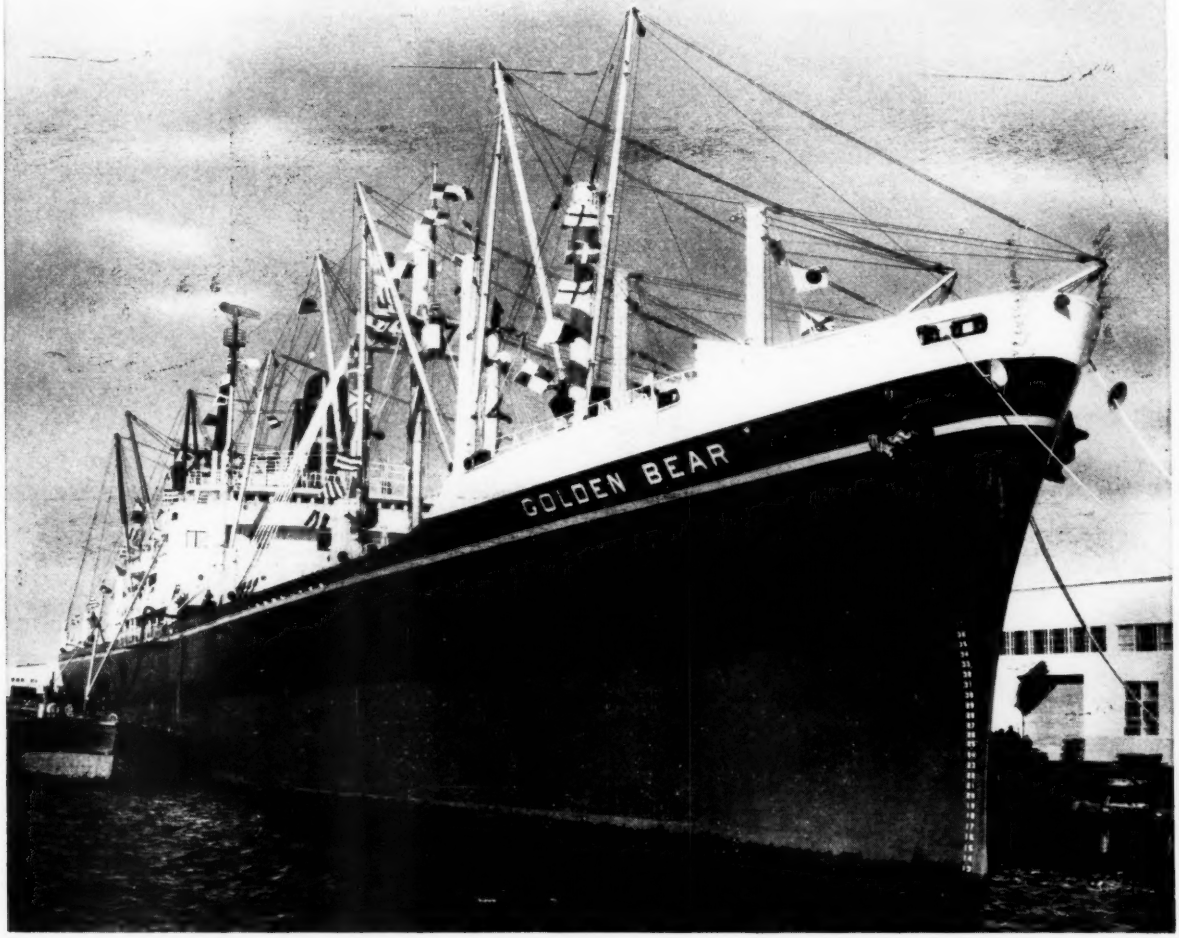
**19,250 shp**

# DE LAVAL *main propulsion unit powers the S S Golden Bear*

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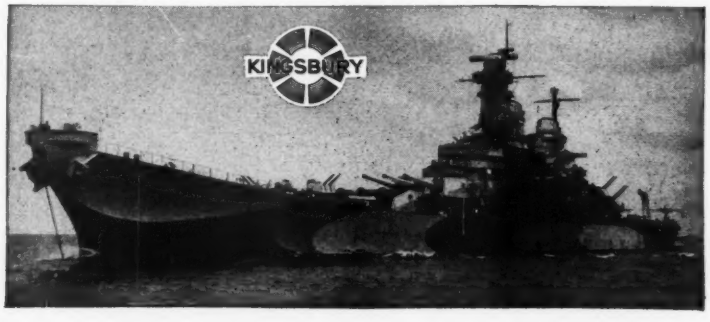


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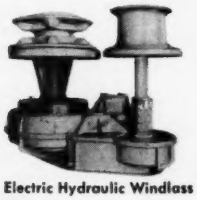
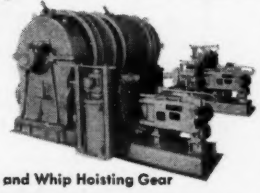
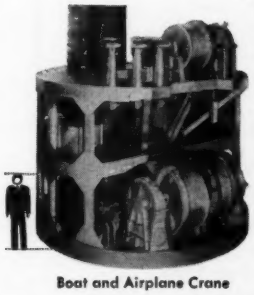


Electric Hydraulic Windlass

Warping Winch



Boat Crane and Whip Hoisting Gear



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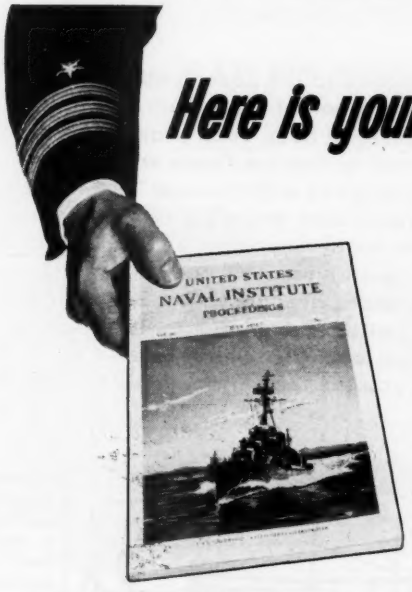


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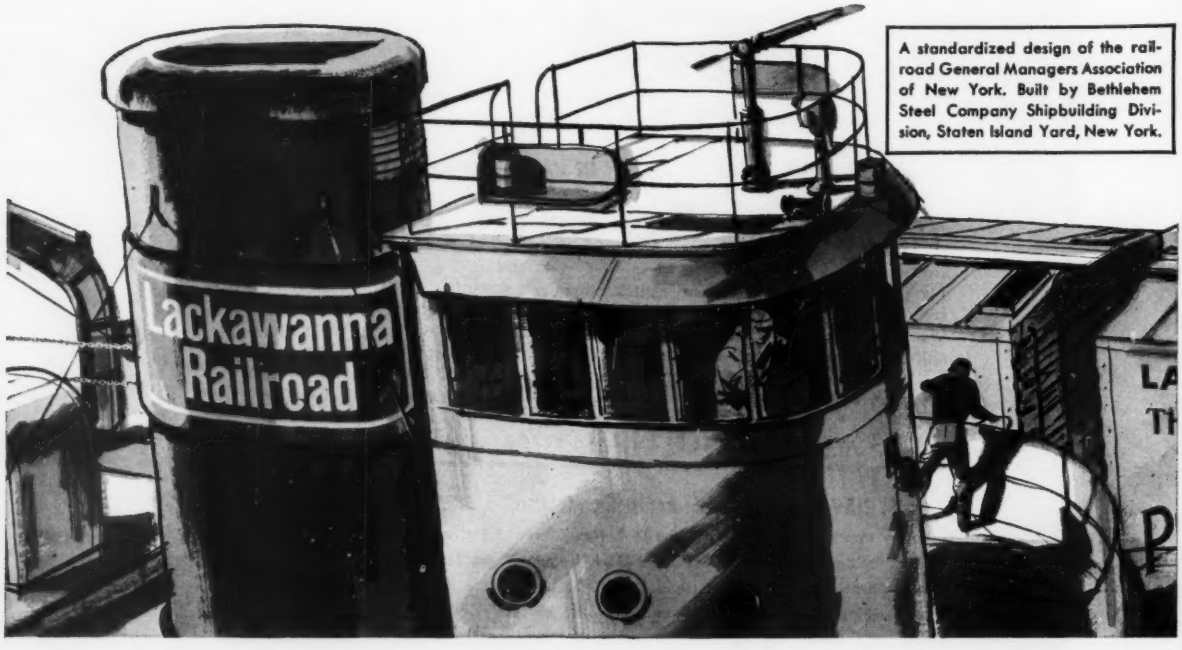


A standardized design of the railroad General Managers Association of New York. Built by Bethlehem Steel Company Shipbuilding Division, Staten Island Yard, New York.

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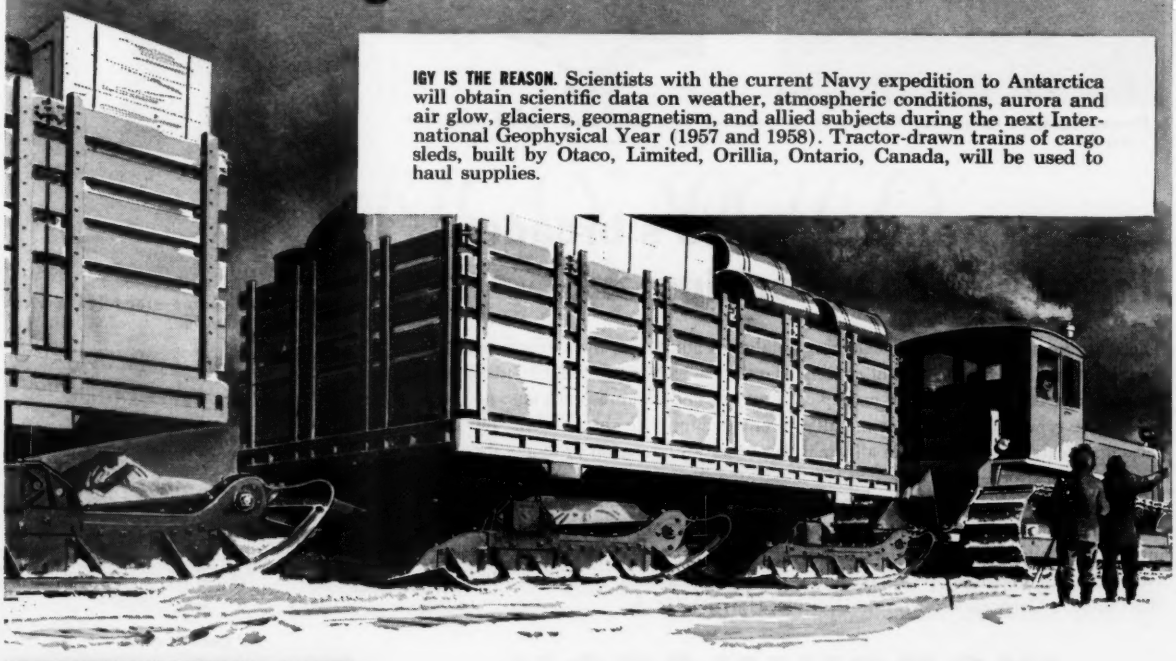
GM CLEVELAND DIESEL

# Operation Deepfreeze sleds plow across Antarctica on tough skis of USS "T-1" Steel

**IGY IS THE REASON.** Scientists with the current Navy expedition to Antarctica will obtain scientific data on weather, atmospheric conditions, aurora and air glow, glaciers, geomagnetism, and allied subjects during the next International Geophysical Year (1957 and 1958). Tractor-drawn trains of cargo sleds, built by Otaco, Limited, Orillia, Ontario, Canada, will be used to haul supplies.



**THE SKIS ARE MADE OF USS "T-1" STEEL.** When the going gets rough, the runners on these cargo sleds are assembled into skis, 13 feet long and 34 inches wide, made of USS "T-1" Steel.

DURING OPERATION DEEPFREEZE, the Navy's current expedition to Antarctica, thirty-eight rugged cargo sleds will be used to haul supplies 400 miles from Little America to Marie Byrd Land. The 11-ton sleds, each carrying a load up to 20 tons, ride on skis made from tough ¼" plates of USS "T-1" Steel. The sleds were designed jointly by the United States Navy and Otaco, Limited, Orillia, Ontario, Canada.

Naturally, the skis had to be made from a steel that stays tough and durable at temperatures far below zero. The steel also had to possess high strength (to keep down weight), and excellent resistance to abrasion (to withstand the 400-mile trip across rugged, ice-covered terrain). In addition, the steel had to have good forming characteristics and be easily weldable (to simplify fabrication).

One steel met all the requirements: that was USS "T-1" Steel. USS "T-1" Steel has a minimum yield strength of 90,000 psi . . . can be welded as easily as carbon steel, with the proper electrodes . . . has excellent resistance to abrasion and impact abuse . . . and remains tough at low temperatures. It was ideal for this tough job.

## A VERSATILE NEW ALLOY STEEL

USS "T-1" Steel is adding strength and durability, cutting weight and costs, in steel mill equipment, power shovels, mine cars, bridges, coal handling equipment, pressure vessels, and many other applications, at high and at low temperatures. It probably can help you improve your own product. Write for complete information. United States Steel, Room 5360, Pittsburgh 30, Pa.

UNITED STATES STEEL CORPORATION, PITTSBURGH • COLUMBIA-GENEVA STEEL DIVISION, SAN FRANCISCO
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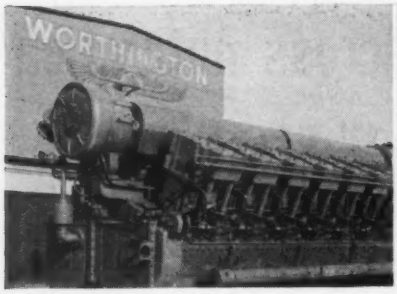
UNITED STATES STEEL SUPPLY DIVISION, WAREHOUSE DISTRIBUTORS, COAST-TO-COAST
UNITED STATES STEEL EXPORT COMPANY, NEW YORK

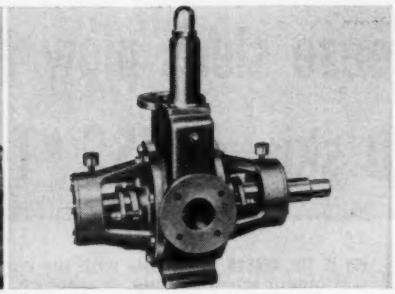
**USS "T-1" CONSTRUCTIONAL ALLOY STEEL**

USS

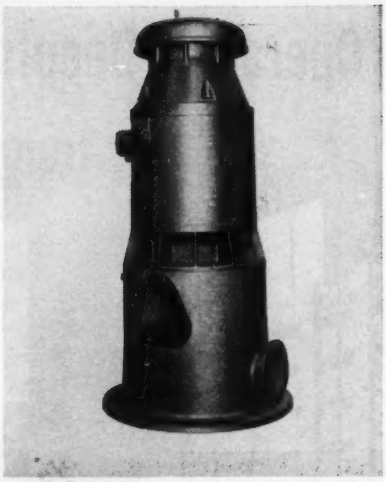
**UNITED STATES STEEL**




**Diesel Engines**—for shipboard service up to 5,000 hp.



**Rotary vane- and gear-type pumps**—for handling oil, gasoline and other liquids.



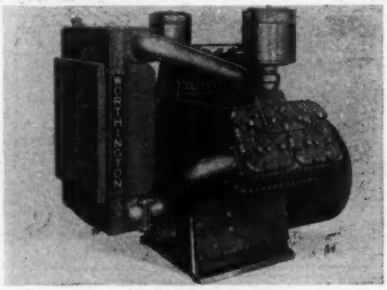
**Vertical turbine pumps**—for bilge service main cargo and stripping.

# Choose from the world's broadest line of shipboard equipment

There are many advantages to selecting shipboard auxiliaries from Worthington's complete line. You can be sure of getting exactly the right equipment to meet your specific requirements. For example, in pumps and compressors alone you have more types than any other manufacturer can supply to choose from. You get the same degree of flexibility in all the many other Worthington products for marine application—some of which are illustrated here.

Worthington welcomes the opportunity to help you with special pumping or power problems. And it offers you the advantage of complete product availability and interchangeability anywhere the world over through the services of foreign Worthington companies. Write, outlining your requirements, to Section M62, Worthington Corporation, Marine Division, Harrison, N. J.

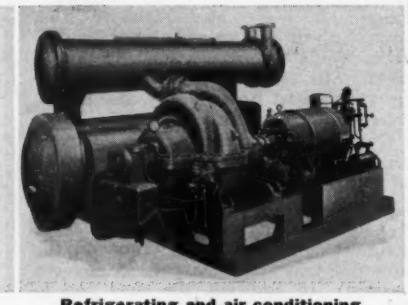
M.6.2



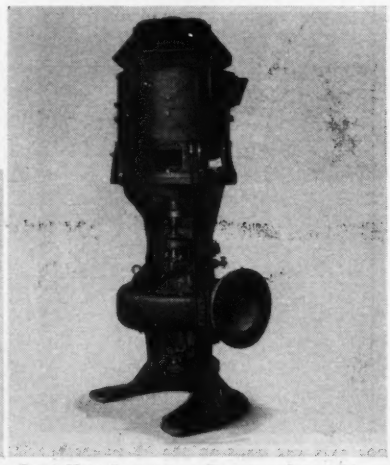
**Air Compressors**

**WORTHINGTON**

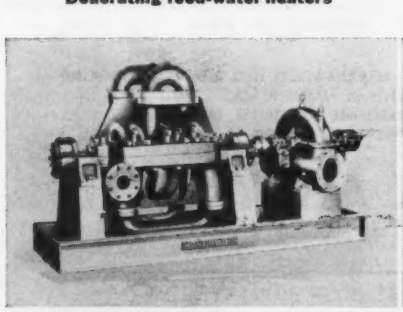
**Deaerating feed-water heaters**



**Refrigerating and air conditioning equipment**

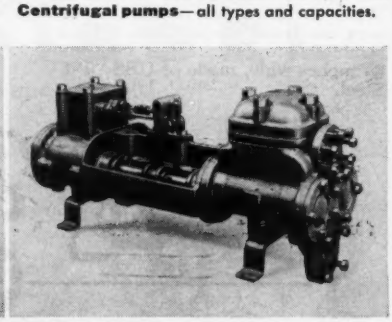


**Centrifugal pumps**—all types and capacities.



**Steam turbines**—single-stage, multi-stage, and combined turbine and gear units.

**Steam condenser and steam-jet ejectors**—for all vacuum services.



**Reciprocating pumps**—steam-driven, motor-driven and variable capacity units.

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# Journal of the AMERICAN SOCIETY of NAVAL ENGINEERS, Inc.

VOLUME 68 | MAY 1956 | NUMBER 2


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(Under whose supervision this number is published)

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Captain PETER V. COLMAR, USCG
Rear Admiral R. E. CRONIN, USN
Rear Admiral L. V. HONSINGER, USN
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Captain J. E. HAMILTON, USN (Ret.), Secretary-Treasurer


## SECRETARY'S NOTES

### Secretary's Apologia

Each year as the May issue of the JOURNAL goes to press, the Secretary-Editor experiences the feeling of relaxation brought about by having completed another cycle. This cycle, of course ends with the post-mortems on the annual banquet and has to do with the May JOURNAL only because of a general coincidence of dates. The month of April is certainly the most crowded with activity (some sweat and tears) around the Society's headquarters.

This last year has been outstandingly epochal in the Society's 68 years. Some of the major events of the year are discussed more fully below. They are:

An entirely new locale for the Annual Banquet.

An entirely new format for the JOURNAL.

Move to the first real office which the Society has ever had.

First Council meeting in the Society's own quarters.

Formal institution of Junior Memberships.

New advertising rate card.

Participation to a modest degree in the Navy's recruiting and reenlistment drive.

Participation, also to a very modest degree, in the Nation's drive to improve technical education.

Around the Society's office we feel that a new maturity has arrived. Holding our own in the 1956 world has forced discard of any feeling of amateurism in the society management and publishing businesses. The staff takes a reasonable amount of pride in the fact that this growing up has been accomplished with no increase in size of staff except for the addition, about a year ago, of a part time secretary, who fortunately, is a very good one.

Members of the Society have every right to feel happy and satisfied in the forward look which its elected Presidents and Councils have taken. Perhaps it should be noted that, in the Secretary's Notes for the issue of November 1948 we mentioned a letter written by Rear Admiral Roger Paine, U.S. Navy who was relinkuishing the office of President through the necessity of being transferred out of Washington. We believe that the events in the Society's life, which we class as advances, should properly be considered as having stemmed from Admiral Paine's letter.

After acknowledging the debt which the Society owes to Admiral Paine, the Society's heaviest creditor is the Administrative Assistant, Mr. Arthur G. Fessenden who is in his forty-eighth year of constant, untiring and loyal service to the Society. As mentioned elsewhere, the members recognized this obligation by conferring lifetime Honorary Membership on Mr. Fessenden and certainly it would be hard to find any individual any where who has more creditably earned this distinction.

**The Annual Banquet—1956**

All of those who regularly attend the Annual Banquet know of its increasing popularity and, hence, size. Fortuitously at about the point where no more could be accommodated in the location where the banquet has been held since World War II, even by setting places in smaller and more remote rooms, the Sheraton-Park Hotel opened its new ballroom. Prior to our banquet on 27 April 1956, this room had been opened for about one year.

Ours, the 38th banquet in the Society's history, was the largest group yet accommodated in the Sheraton-Park for a dinner of this kind and will rarely be exceeded. The maximum capacity which can possibly be squeezed in appears to be an even 2000. Our seating list carried 1986 names.

1956 definitely marks the year of our largest banquet and the largest similar affair probably ever held in Washington, D.C. The necessity of rejecting applications in the future looms large because there is no room for growth unless a new and larger facility is built and put into operation.

The 1956 banquet has more than size to commend it. The dinner was excellent and the program better received than many previous ones have been. The menu and the program are printed on page 211.

As a revived feature, abandoned for many years, photographs were taken. These are reproduced in this issue of the JOURNAL.

The President of the Society, Rear Admiral Kenneth K. Cowart, U.S. Coast Guard, presided and with the performance of Rear Admiral A. G. Mumma, U.S. Navy who acted as toastmaster, conducted a most enjoyable program. We have been unable to find in our records any previous occasion when the Engineers-in-Chief of the country's two military maritime operating activities, jointly conducted an American Society of NAVAL ENGINEERS banquet. Admiral Cowart's remarks are published on page 217.

The senior official from the Washington hierarchy who occupied the dais was the Honorable Wilfred J. McNeil, Assistant Secretary of Defense and Comptroller of the Department of Defense. Long a friend of the Society, Mr. McNeil expressed a few words of appreciation. Mr. McNeil is unique in being the only member of the Defense Secretariat who has ably served the last two administrations. He may also be recognized as one who tempered the storms which have threatened to arise over partition of the Defense budget between the three services. The outline picture of the USS *Forrestal* which we used on the banquet program replaced one which was used for several years. That one was of the USS *United States* which did not progress much beyond a keel. Mr. McNeil was a party to the pre-birth of both of these ships.

The principal address entitled "The Mutual Influence of Sea Power and Future History," by Admiral Robert B. Carney, U.S. Navy, Retired, recently Chief of Naval Operations which office was preceded by a long and brilliant and publicly recognized naval career, is printed in full, following Admiral Cowart's and Mr. McNeil's remarks. This talk was profound.

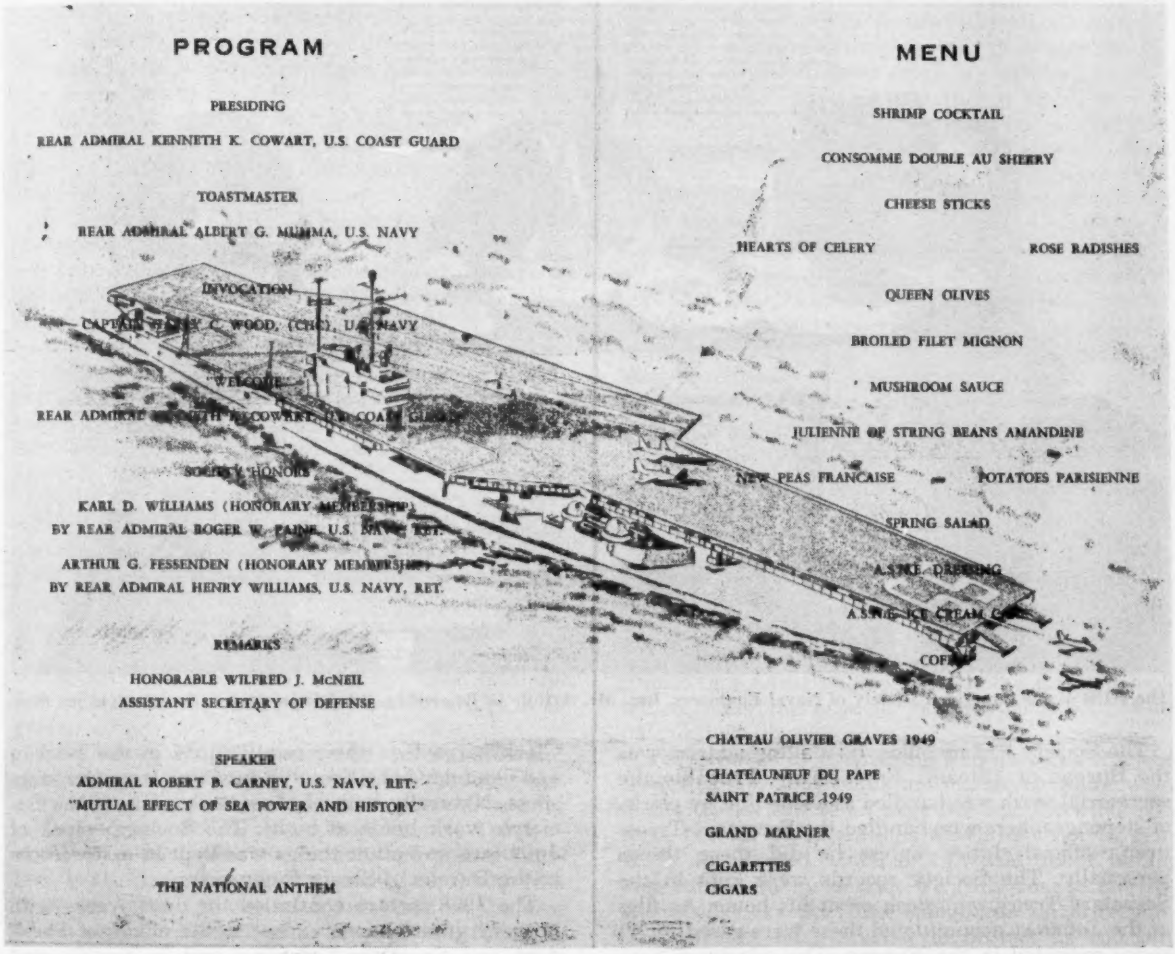
Upon going to press, we feel that the 1956 banquet was highly successful. Final post-mortems have not been conducted so we are not in a position to report that it was perfect. Experience has shown that any flaws which are brought to the attention of the Committee will not recur next year. Naturally, that remark cannot pertain to the unfortunate circumstances that 1500 people who attended would have preferred better seats. That is a natural characteristic of any gathering of 2000 and our Committee cannot battle nature.

Because of the change in location of the banquet, the Council a year ago requested the 1955 committee to serve for an additional year so that their experience might be fully utilized. Those still in Washington readily agreed and accepted the arduous task of perfecting arrangements. This committee was composed of:

Mr. J. B. Armstrong
Captain R. M. Barnes, USN
Commander C. H. Campbell, USNR
Mr. Francis H. Engel
Mr. Arthur G. Fessenden
Mr. M. D. Gibson, Jr.
Captain J. E. Hamilton, USN, Ret., Chairman
Mr. Edward G. Haven
Captain R. B. Madden, USN
Captain W. R. Millis, USN, Ret.
Commander Ivan Monk, USN
Commander J. W. Naab, USCG
Mr. William N. Ruby
Mr. Mark Swanson.

In the Chairman's opinion particular credit is due to Mr. M. P. Gibson, Jr., Chairman of the Arrangements Sub-committee and, again for the 38th time, to Mr. Fessenden who handled all of the paperwork, finances and records as usual.

## ANNUAL BANQUET
### The Sheraton-Park Hotel, Washington, D.C., 27 April, 1956



PROGRAM

PRESIDING

REAR ADMIRAL KENNETH K. COWART, U.S. COAST GUARD

TOASTMASTER

REAR ADMIRAL ALBERT G. MUMMA, U.S. NAVY

INVOCATION

CAPTAIN [illegible] C. WOOD, (CHC), U.S. NAVY

WELCOME

REAR ADMIRAL [illegible] COWART, U.S. COAST GUARD

SOCIETY HONORS

KARL D. WILLIAMS (HONORARY MEMBERSHIP)
BY REAR ADMIRAL ROGER W. PAINE, U.S. NAVY, RET.

ARTHUR G. FESSENDEN (HONORARY MEMBERSHIP)
BY REAR ADMIRAL HENRY WILLIAMS, U.S. NAVY, RET.

REMARKS

HONORABLE WILFRED J. McNEIL
ASSISTANT SECRETARY OF DEFENSE

SPEAKER

ADMIRAL ROBERT B. CARNEY, U.S. NAVY, RET.
"MUTUAL EFFECT OF SEA POWER AND HISTORY"

THE NATIONAL ANTHEM

MENU

SHRIMP COCKTAIL

CONSOMME DOUBLE AU SHERRY

CHEESE STICKS

HEARTS OF CELERY ROSE RADISHES

QUEEN OLIVES

BROILED FILET MIGNON

MUSHROOM SAUCE

JULIENNE OF STRING BEANS AMANDINE

NEW PEAS FRANCAISE POTATOES PARISIENNE

SPRING SALAD

A.S.N.E. DRESSING

A.S.N.E. ICE CREAM [illegible]

COFFEE

CHATEAU OLIVIER GRAVES 1949

CHATEAUNEUF DU PAPE
SAINT PATRICE 1949

GRAND MARNIER

CIGARETTES
CIGARS

**Suite 1004, The Continental Building**

We have included several pictures of the Society's new quarters in Suite 1004, the Continental Building, 1012 14th St., N.W., Washington, D.C. For the first time, the Society has an office where members and guests can be welcomed without excuse for the surroundings. The pictures were taken during the Council-meeting on 6 March 1956.

**An Historic Occasion**

As the Council met on 6 March 1956 it suddenly occurred to us that this was the first meeting, in the Society's lifetime of more than 67 years, which was held in offices which the Society could call its own. This thought led to a discussion which brought out the following bit of history.

**Progress of Growth and Maturity—
One Type of Measure**

All of this cannot be documented but it is believed to be reasonably accurate.

When the American Society of Naval Engineers was organized in 1888, its business, as today was conducted by the Secretary-Treasurer under the direction of the Council. The first person elected to the office of Secretary-Treasurer, who was also editor of the JOURNAL, was Past Assistant Engineer R. S. Griffin, U.S. Navy. He served in 1889, 1894 and 1895. He also served as President in 1908, 1912, 1913. He is probably best known as Rear Admiral Griffin, Chief of the Bureau of Steam Engineering during World War I.

Griffin and his successors for many years were officers on duty in Washington in the Bureau of Steam Engineering or its successor, the Bureau of Engineering.

For the first 15 years, how the Society funds were protected is not a matter of record. Its first bank account was established in 1903 by the then Secretary, Lieutenant Commander John R. Edwards, U.S. Navy. Presumably, until that time the money was carried in a personal account.

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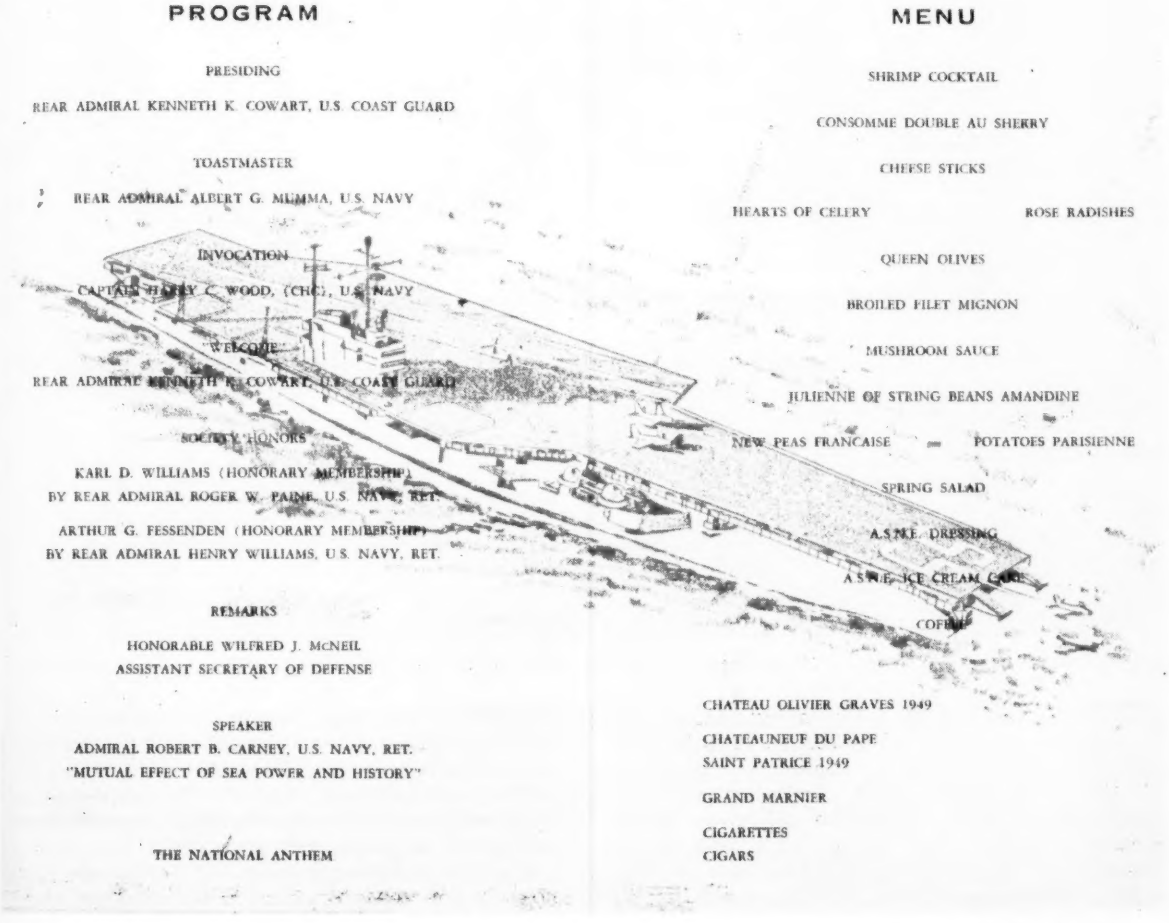

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**The HUB of the American Society of Naval Engineers, Inc., Mr. Arthur G. Fessenden, the Administrative Assistant, at his desk.**

The Society had no office. Its mailing address was the Bureau of (Steam) Engineering. Probably the secretarial work was handled as a side line by clerks of stepongraphers who handled the Secretary-Treasurer's official duties unless he did these things personally. The Society records were kept in the Secretary-Treasurer's desk or at his home. As files of the JOURNAL accumulated these were cared for in space provided in the Bureau. This condition continued until the pre-World War II expansion of the Navy Department placed such a premium on every square foot of space that the Society had to find other storage space. We will return to that later.

The books were kept by the Secretary himself, in at least one case, in a small pocket notebook. This was practicable up to a certain limit which was apparently reached in 1908.

In November 1908 during the second annual term as Secretary-Treasurer of Lieutenant Commander T. C. Fenton, U.S. Navy, the Society hired a part time clerk. This young man took over the bookkeeping, filing and typing of the Society and established the Society's working office as a split between the desk in the Bureau where he was regularly employed and his home. This man was a Government Civil Servant in the Bureau—his name Arthur G. Fessenden.

This was the picture in 1908. The President used his regular office in the Bureau and Council meetings were presumably held there. The Secretary and the Clerk carried on their regular jobs in the Bureau and conducted the Society's business from the same spots. Naturally both of these took some of the Society's work home at night. The Society's stock of JOURNALS and other things was kept in a storeroom in the Bureau of Steam Engineering.

The 1908 picture continued for many years with no very great change except in the offices of President and Secretary-Treasurer and in the Council membership. During the first 20 years (1888–1908) 13 different officers served as President and 12 as Secretary-Treasurer. There was no one else except the Council. During the next 30 years, 19 additional officers were elected to the Presidency and 18 to the Secertary-Treasurership. *The Clerk remained unchanged.*

In 1938 the expansion of the Bureau which was mentioned squeezed the Society's storeroom out of government space. As a convenience, to the Society, Mr. Fessenden provided space in his home to accommodate the accumulation of 50 years except for the file of bound volumes of the JOURNAL which moved around the Bureau to follow the election ballots for Secretary-Treasurer.

At about this same time, the Council appointed an Assistant Secretary-Treasurer to help in the editorial work of the JOURNAL. Mr. Fessenden had not assumed any of the Editorial work so for 50 years this had been conducted pretty much alone by the Secretary-Treasurer. This officer had received clerical

assistance after 20 years and editorial assistance after about 50.

Five years later the double job which he was carrying became so heavy that Mr. Fessenden had to drop one or the other. His devotion and loyalty to the Society led him to retire from his Civil Service position to devote full time, at an appreciable financial sacrifice, to his job as A.S.N.E. Clerk. At that time the Society's office very definitely moved to Mr. Fessenden's home although the mailing address was still kept at the Bureau of Ships.

In another five years, Mr. Fessenden gave up his home and moved to an apartment. The Society's gear was moved to a room which was rented, at a very nominal sum, from our printer R. Beresford and the Society address was changed to 605 F. St., N.W. The space occupied was voluminous enough to house all of the Society's stores and files and principal piece of furniture, THE DESK. This article had served for about 35 years with our Clerk and from its second-hand price of 15 dollars had been amortized to zero for many years.

In 1954 circumstances forced a change of printers. Although we remained in the Beresford building an early change was indicated. Before this happened, the clerical load which had forced Mr. Fessenden's retirement from Civil Service, through continued expansion forced the employment of a part time Secretary for Mr. Fessenden. Of course, that mushroomed into the need for a second desk and the Society acquired its first piece of *real* furniture in 60 years.

The Council in 1955 considered the situation and circumstances thoroughly and decided that the Society had now grown up. It was time for it to be fully self-supporting. It authorized the Secretary-Treasurer to locate and move to adequate and proper quarters. It also transferred not to exceed $5,000.00 from the reserve fund to capital account so that the new offices could be furnished in keeping with the prestige of the Society.

These quarters were found and were occupied on 23 November 1955 just a few days before the wreckers moved in to raze 605 F. St. and just an hour after the original Society desk collapsed. The cost of the move and furniture was about one-half of the amount authorized.

The pictures in these Notes show something of the layout and appearance of Suite 1004, The Continental Building. One of them shows the Council members who attended the first meeting ever to be held in THE SOCIETY'S OWN QUARTERS. It took 67 years but we believe that it is worth it, and also worthy.

**Power Generation and ASNE**

One member has suggested that the JOURNAL increase its coverage of nuclear power developments. It was no coincidence that the Council had already reached this decision for a reason which is basic to the foundation of the Society.

In its 67 volumes, the JOURNAL can be followed as a positive guide to the forms of power generation and transmission, particularly of course, in marine applications. The transition from the Scotch Boiler to the Nuclear Reactor and from the compound horizontal engine to a steam or gas turbine which can receive and transform the product of the nuclear reactor with contemporary accomplishments of diesel and other internal combustion engines and gas turbines has been pretty well chronicled since 1888. At least one reader has expressed the fear that we were overdoing the assignment of space to nuclear matters. We do not agree. In a very real sense, the advances of technology have been accelerating along an exponential type growth curve. We find that our efforts to expand the JOURNAL at a corresponding rate in order to cover every field wherein new things challenge the naval engineer is impossible. However, in the field of ship propulsion, to adhere to the dreams of the founders of the Society, we cannot afford to stint. We shall continue to seek out worthy reprints and to accept original articles on nuclear power subjects and will devote enough space in the JOURNAL to their proper display.

Attention is invited to the Book Review by Mr. Mark Ireland on page 399. It appears that the U.S. Atomic Energy Commission is committed to a course which will make engineering experience and data information in the nuclear field available to the public in a comprehensive and timely manner. It is assumed that naval engineers with the forward look will consider the need for adding the A.E.C. Manuals to their libraries.

Very vital to us in covering a subject like Nuclear Power in the JOURNAL is the matter of military security. In an article on page 307 Mr. Detwiler sets forth certain considerations which may not be generally appreciated. Much as we would like to obtain and publish many details, we fully realize our responsibility to support the safeguards which responsible officials have erected to protect us and our country. Any knowledge or information which is responsibly considered properly to be on a "need to know" basis is something that we as publishers of the JOURNAL do not need to know nor can our readers expect to get such information from our pages.

It is all of 25 years since the JOURNAL has been able to print in detail the full Engineering Trial Reports of new naval ships. Up until 1933 these reports filled many pages. In that year clearanace to publish was denied for the first time.

We would enjoy a world environment where anyone who knew anything could write about it and we could become the medium wherein naval engineers could read about the very latest and best in full scientific or engineering detail. Manifestly the present environment is not like that.

**Codes of Ethics**

In their efforts to establish engineering as a pure profession, many engineering societies have adopted codes of ethics to govern the conduct of their members. This Society has been asked to subscribe to

**The historic Council meeting of Tuesday, 6 March 1956. Seated: Mr. A. G. Fessenden, Administrative Assistant; Rear Admiral Kenneth K. Coward, U. S. Coast Guard, President; Captain J. E. Hamilton, USN, Ret., Secretary-Treasurer. Standing (Members of the Council): Lieutenant Commander J. W. Sawyer, USNR; Mr. James S. Melton; Rear Admiral L. V. Honsinger, USN; Captain Peter Horn, USN; Mr. Thomas H. Shepard, Jr.; Captain Peter V. Colmar, USCG.**

**The President and the Secretary-Treasurer scan the entrance to Suite 1004.**

**The Administrative Assistant and the Secretary-Treasurer at the door of their offices.**

such codes but has felt that its nature makes this action unnecessary. "Naval Engineering" has become a composite or compound term. It is really the *application of any kind of engineering* to naval purposes. Most "Naval Engineers" are educated and classed as mechanical, electrical, electronics, etc. engineers. Naval Architects as engineers are also "Naval Engineers." These individuals who join the American Society of Naval Engineers are under a dual compulsion as regards ethics. These are imposed by the codes of their particular professional society on the one hand and the traditional codes of ethics of the public servant and of the Naval Service on the other. For this reason this Society feels that the restraints and policing which adoption and enforcing a special code on our members implies is not necessary.

However, as publishers of the JOURNAL we have another sort of obligation which is to our advertisers. The article "Dangers Ahead for the Engineering Profession" which we reprint on page —— describes this. We have never set aside a section of the JOURNAL for "Professional Cards" but will be happy to do so immediately on request of anyone who wishes to insert a professional card. Until we have gained experience and made a further study of the matter, we will change regular advertising space rates for these cards.

**Scientific and Engineering Education**

Joint Engineering Councils and many others have made the public aware of the critical situation with which the United States is faced in regard to the number of scientific and engineering college graduates. The pages of the JOURNAL have been made available so that the Society may contribute to the campaign which is designed to improve the situation.

We feel that the article on page 259 by Rear Admiral Hyman G. Rickover, U.S.N. is a very valuable contribution to this campaign.

**Navy Recruitment and Reenlistment Program**

Another campaign of great national importance is that of the Navy in trying to improve the numbers of voluntary enlistments and reenlistments.

On page 220 is a succinct statement about the United States Navy, its role in national defense, the importance of the individual in the Navy, and the future of the Navy. It has been approved by the Chief of Naval Operations and represents the corporate thinking of mature and experienced officers of the Navy.

In today's New Navy the individual is increasingly important, and a common understanding of the role and mission of the Navy should be constantly kept in mind by all members of the Naval Establishment from Seaman to Admiral.

Today the U. S. Navy is the world leader in the utilization of atomic power in the *Nautilus*, and in new ship developments, is in the forefront in guided missile development and is a leader in the whole aviation development field. Such preeminence is comforting in today's troubled world and augurs well for the New Navy now being developed.

**Engineering Societies**

The U.S. Department of Commerce is preparing a Directory of Engineering Societies. A preliminary draft carries the names of 65 such societies. We were interested in our place on this list and arranged the entries chronologically with the following results:

| | *Established* |
|---|---|
| 1. American Society of Civil Engineers | 1852 |
| 2. American Institute of Mining and Metallurgical Engineers | 1871 |
| 3. American Chemical Society | 1876 |
| 4. American Society of Mechanical Engineers | 1880 |
| 5. National Association of Power Engineers | 1882 |
| 6. American Institute of Electrical Engineers | 1884 |
| 7. AMERICAN SOCIETY OF NAVAL ENGINEERS | 1888 |

Seven more societies were formed in the 19th century since which these formations have occurred at an average rate of ten per decade.

This chronology appears to indicate that the officers of the old Naval Engineers Corps were among the very first to recognize the great potential contributions of joint action and joint attack on technological problems. We mid-twentieth century followers to whom this torch has been passed are attempting, in the JOURNAL, to prove the soundness of their views.

**Errata**

At the top of the first column, page 48 of the text of "Power Reactors" by Robert W. Clack the statement ". . . metallic uranium rods clad in an aluminum jacket . . ." appears. The author points out in a letter to the Editor "that the use of aluminum is confined to lower power or research reactors in the indicated application. The cladding material used on the fuel elements in power reactors must have a considerably higher melting point than can be had with aluminum or aluminum alloys. A satisfacotry material for cladding in power reactors is zirconium or zirconium alloy."

**The Journal**

Mod. 1 of the new format cover clothes this issue of the JOURNAL. This represents a composite of many suggestions which were received after the February issue appeared. Further comments and suggestions regarding the cover or any other feature of the JOURNAL are sincerely desired.

**Death of Miss Elizabeth Beresford**

We have commented previously on the very great contributions which were made to the JOURNAL by Miss Elizabeth Beresford who handled our printing for 25 years. She succeeded her father who had served this role for the preceding 30 years.

It is with deep and sincere regret that we report the death of Miss Beresford.

**BANQUET, AMERICAN SOCIETY OF NAVAL ENGINEERS, APRIL 27, 1956**

**The best overall photograph which could be taken. Other tables are on the balcony and to the right and left of and behind the photographer, under the balcony.**

**Opening Remarks**

Opening Remarks at the Annual Banquet of The American Society of Naval Engineers, Friday, April 27, 1956, by its President, Rear Admiral Kenneth K. Cowart, U. S. Coast Guard:

Prior to turning the meeting over to our toastmaster, I would like to make a few brief remarks.

It is indeed a great honor for any officer to be elected President of this Society. Having been elected your President as a Coast Guard officer, our number being rather small, I feel very specially honored and very flattered. I also feel that the real credit properly belongs to my contemporaries, and predecessors, in the Coast Guard, all of whom have served so faithfully and to whom I owe so much. I want *all* of you, and the entire membership, to know that I shall always regard my service as President of this Society as one of the most cherished honors of my life.

Our Society fills an important national need, in its relationship to the naval growth and history of our country. In addition, it fills an important professional and social need for each of us who are members.

As you all know, the annual activity of our Society may be measured by five items, namely, four issues of the JOURNAL, and this, our annual banquet. Referring to the JOURNAL, I am sure the membership has noticed recent changes, which have been directed toward general improvement. Not only has the format been changed, to keep pace with the current advancing tempo, but the professional level of the substance of the articles has been considerably improved. This is very fitting and in harmony with the general and rapid technological advances of our time. Another change, the establishment of a junior membership in the Society, was made during the past year. We are hopeful that this change will strengthen our membership with young blood, by encouraging our engineers to become members while they are still young. I would like to say that these changes have *not* been made as the result of my efforts. My predecessor, Rear Admiral F. R. Furth, his predecessors, the members of the Council, and their predecessors, the contributors to the JOURNAL, a cooperative membership, our Assistant Secretary-Treasurer, Captain Madden, our Administrative Assistant, Mr. Fessenden, and our Secretary-Treasurer, Captain Jimmy Hamilton, are due the credit.

To continue with some further changes during the past year, it was only a short while ago, on March 6 in fact, that the Council of the Society held a meeting which was historic in character. It was historic because it was the first meeting of the Council in the new permanent quarters of the Society, which are located in the brand new air conditioned Continetal Building, at 1012 Fourteenth Street, N.W., Washington, D. C. The next issue of the JOURNAL will feature some pictures of these new quarters, along with a little history of the Society's earlier quarters and furnishings. However, I would like at this time to extend a cordial invitation to all members to drop in at our new quarters and pay us a visit. Our Secretary-Treasurer, Captain Hamilton, and our Administrative Assistant, Mr. Fessenden, both join me in extending this cordial invitation to all members, as well as their guests.

It was during this same meeting, on March 6, that another important event occurred. The Council presented to the widow of Mr. Edward C. Magdeburger, a Certificate of Honorary Membership. Mr. Magdeburger joined the Society in 1925, and was an active member until his death, contributing many articles to the JOURNAL. On 4 October 1955, he was nominated for Honorary Membership with the following citation:

> "In view of his considerable contribution in the diesel engine field, his leadership and vigor in the adoption and use of diesel engines by the U. S. Navy, his inspiration and guidance to the many Naval Engineers and young officers who worked with him, and his outstanding performance as a good citizen, the Council of the American Society of Naval Engineers takes great pleasure in directing that Mr. Edward C. Magdeburger's name be printed on the ballot for the 1956 election of officers with recommendation for election as an Honorary Member."

His name was before the Society for election to Honorary Membership at the time of his death. The vote of the membership was overwhelmingly in favor of his election to Honorary Membership.

The membership also voted to have certificates of Honorary Membership presented to two other of our members. I would like at this time to call on one of our past presidents, Rear Admiral Roger W. Paine, USN (Retired), to deliver the first certificate to Mr. K. D. Williams. As many of you know Rear Admiral Paine was a former Secretary of the Society, and in 1948 he was our President. On termination of his duties as President he wrote a very eloquent and constructive letter to the Council at the time, which was the basis and beginning of an improvement program, some recent particulars of which we've spoken about tonight. It's a pleasure to present Rear Admiral Roger W. Paine, U.S. Navy (Retired).

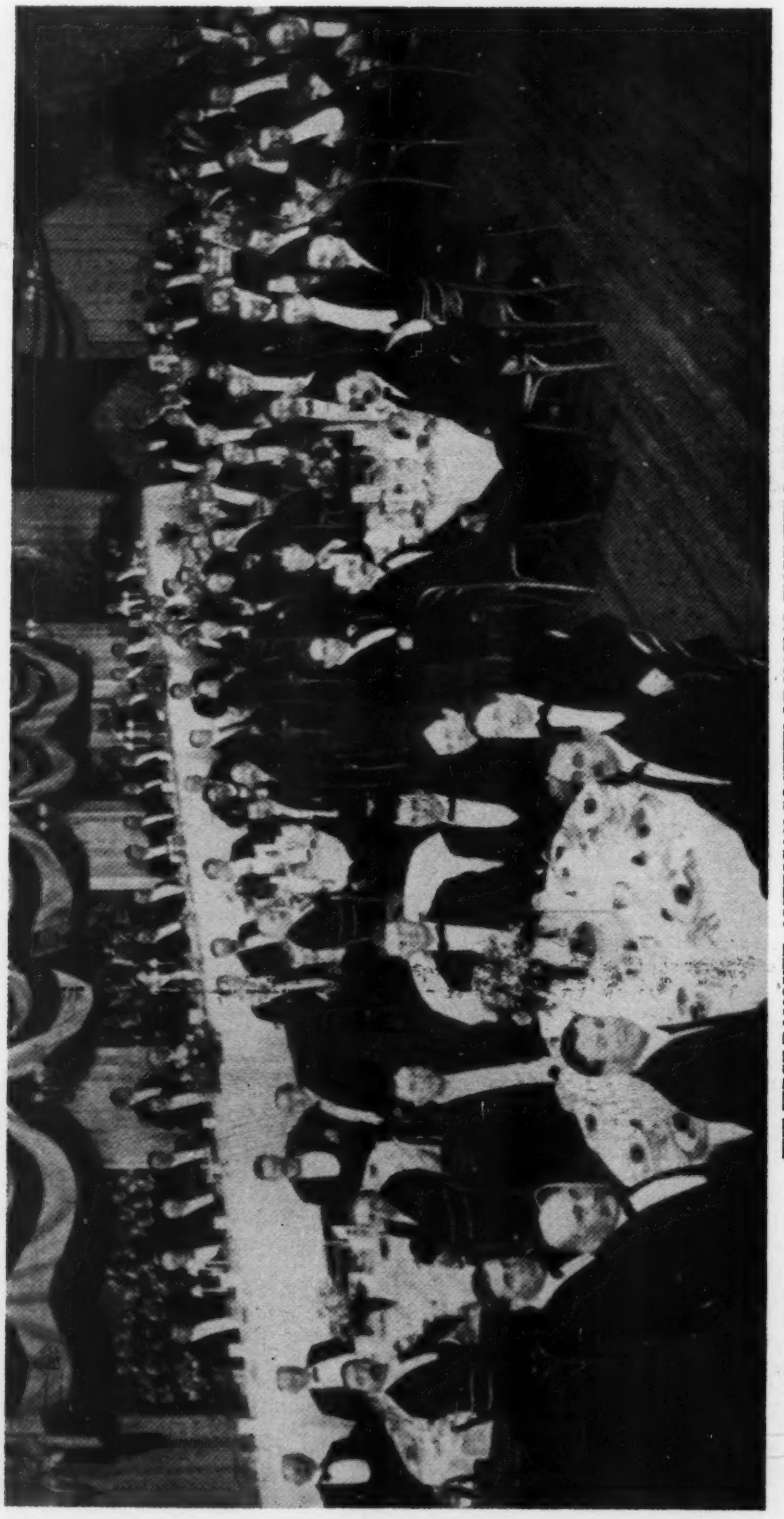
*(Admiral Paine presented the Certificate of Honorary Membership. It was accepted in behalf of Mr. Williams, who was unable to attend on account of health, by Captain Hamilton.)*

Now, I would like to call on one of our past presidents, who is not our oldest past president, but is the oldest one present here tonight in point of his time as president, to deliver the second Certificate of Honorary Membership to Mr. A. G. Fessenden, our Society's Administrative Assistant. Rear Admiral Henry Williams served as President in 1940, and has the distinguished honor of being the first Naval Constructor to serve as President. It is a pleasure to present Rear Admiral Henry Williams, U. S. Navy (Retired).

*(Admiral Williams presented the Certificate of Honorary Membership to Mr. Fessenden.)*

And now, before turning the meeting over to our Toastmaster, I would like to *again* extend a hearty welcome to all our members and guests.

The Coast Guard and the Navy have always maintained a very close, and cooperative, relationship. This is especially true in Washington between Coast Guard Engineering and our good friends in the Bureau of Ships. Tonight this is well illustrated by the fact that we have the Chief of the Bureau of Ships as our Toastmaster. When I asked Admiral Mumma if he would so serve, I was very pleased that he readily agreed. Naturally, he needs no introduction to this audience. Gentlemen, the distinguished and able Chief of the Bureau of Ships and our Toastmaster of the evening, Rear Admiral A. G. Mumma, U. S. Navy.



THE FIRST BANQUET, AMERICAN SOCIETY OF NAVAL ENGINEERS, MAY 7, 1909

Remarks of Honorable W. J. McNeil, Assistant Secretary of Defense (Comptroller), before the Annual Banquet of The American Society of Naval Engineers, Washington, D. C., April 27, 1956:

It is always a great pleasure for me to meet with the members of the American Society of Naval Engineers and to participate in your annual dinner. I believe this is the 10th affair of this type which I have attended, and I must say I have enjoyed every one of them. I have never lost my country-boy enthusiasm for ships and the people who build them.

I find myself tonight in the situation of the Admiral who ran into a boyhood rival at the Railroad station. Like the Admiral, his rival who had entered the Church, had also enjoyed considerable success in his chosen field since they last met. He was now a Cardinal with a considerable paunch and was dressed in the vestments of his office. Upon seeing the Admiral sitting on a bench waiting for his train, he rushed over and shouted: "Porter, can you tell me on what track the train to New York is leaving?" The startled Admiral looked up and, recognizing his old boyhood rival, said: "The train to New York leaves on track 9, but, Madame, I don't think you are in a condition to travel."

In condition or not, I have a few thoughts concerning the past and future of Naval Engineering which I would like to express.

Naval engineering, it seems to me, stands today in a position not unlike that faced at the time the American Society of Naval Engineers was founded in 1888.

The second half of the 19th Century marked the coming of the Machine Age to the Navies of the world. The industrial revolution in sea power had begun earlier in that Century with the introduction of the steam engine as an auxiliary source of power to the sail. But the real age of steam was yet to come. The structural limitations on the size of ships which could be built of wood served as a barrier to the full exploitation of the marine steam engine. It was the coming of the iron and steel hull which broke this barrier and made possible the larger ships so sorely needed for the full exploitation of the potentials of the steam engine and which in time opened the door to effective armor and heavy ordnance, the technical prerequisites of a modern Navy of the recent past.

From the end of the Civil War until the early 1880's, the U.S. Navy experienced a period of absolute decline. New ship construction during this period was negligible, and consisted mostly of wooden ships. The basic industry needed for a modern Navy did not exist in this country. Navy policy at that time was oriented to commerce raiding and passive coast defense for which wooden sailing ships and ironclads were then deemed suitable.

It was not until 1881, only seven years before the Society was founded, that the U.S. Government took an official interest in the development of a modern Navy. Two years later the Congress voted the construction of three protected cruisers and one dispatch boat to be constructed of steel and to be propelled by steam with auxiliary sails. These were the *Atlanta, Boston, Chicago* and *Dolphin,* the famous A, B, C, D ships which marked the beginning of the modern U.S. Navy. They were delivered in the period 1885 to 1887 and were formed into what the Navy at that time called a "Squadron of Evolution"—popularly known as the White Squadron.

In 1886, just two years before the Society was founded, the Congress decreed that the Navy use in the construction of naval vessels only materials of domestic manufacture. This delayed the construction of the new Navy, but it laid the foundation of the great supporting industry upon which our Naval power rests to the present day.

It was just about this time, 1890, that Admiral Mahan's famous work, *The Influence of Sea Power Upon History,* was published. This work furnished the philosophical basis and gave direction to America's gropings for a modern Naval policy. In the same year, the Congress gave practical expression to the theories expounded by Admiral Mahan by voting funds for the construction of three "sea-going" battleships, the *Indiana,* the *Massachusetts,* and the *Oregon.*

I need not recount to this audience the rapid development of Naval engineering which then ensued. The size, variety and efficiency of steam engines expanded very rapidly, followed later by the introduction of the steam turbine, the marine diesel engine, turbo electric propulsion, etc. At the same time, auxiliary engines of all types for steering, gun turrets, anchors, pumps, ammunition handling, etc., continued to multiply. The size, speed and combat power of our warships continued to grow and the submarine, the aircraft and the carrier made their appearance.

Now, almost without public notice, we are entering a similar period of revolutionary development in naval engineering—nuclear energy as a source of propulsion power, guided missile armaments, new hull designs as symbolized by the *Albacore* and the extensive application of electronics to all phases of ship operation.

No one can clearly foresee where all these dramatic developments will lead, but we may be sure that the Navy of the future will be a much more powerful and versatile force than it is today.

While the Naval Engineering fraternity may well look back on past achievements with great satisfaction, it seems to me that even greater challenges lie ahead.

# THE UNITED STATES NAVY

## GUARDIAN OF OUR COUNTRY

The United States Navy is responsible for maintaining control of the sea and is a ready force on watch at home and overseas, capable of strong action to preserve the peace or of instant offensive action to win in war.

It is upon the maintenance of this control that our country's glorious future depends; the United States Navy exists to make it so.

## WE SERVE WITH HONOR

Tradition, valor, and victory are the Navy's heritage from the past. To these may be added dedication, discipline, and vigilance as the watchwords of the present and the future.

At home or on distant stations we serve with pride, confident in the respect of our country, our shipmates, and our families.

Our responsibilities sober us; our adversities strengthen us.

Service to God and Country is our special privilege. We serve with honor.

## THE FUTURE OF THE NAVY

The Navy will always employ new weapons, new techniques, and greater power to protect and defend the United States on the sea, under the sea, and in the air.

Now and in the future, control of the sea gives the United States her greatest advantage for the maintenance of peace and for victory in war.

Mobility, surprise, dispersal, and offensive power are the keynotes of the new Navy. The roots of the Navy lie in a strong belief in the future, in continued dedication to our tasks, and in reflection on our heritage from the past.

Never have our opportunities and our responsibilities been greater.

ADMIRAL ROBERT B. CARNEY

# *THE MUTUAL INFLUENCE OF SEA POWER AND FUTURE HISTORY*

*An address before The American Society of Naval Engineers, Inc., by Admiral Robert B. Carney, United States Navy Retired, Friday, April 27, 1956*

Mahan did much to codify the political importance of sea power when he analyzed past history in terms of sea power's influence. Our own generation witnessed events which clearly emphasized the essentiality of sea power in a great struggle and pointed up the dangers of extended geopolitical ambitions when unsupported by an ability to control essential parts of the seas. Now, mankind is anxiously preoccupied with the future and is endeavoring to identify and sort out the factors which will determine the success or failure of the objectives of the great human forces at work throughout the world; dynamic philosophies and aspirations are in conflict, everywhere the stakes are high and the dangers are great. The sea will play its part and advantage will accrue to the side which best understands and utilizes the potentials of sea power.

Science is whizzing at a bewildering rate and the leadership of the world has become infinitely complicated. Governments concerned with global strategy have a task complicated far beyond anything which confronted their predecessors; not only are the interrelations of governments becoming more complex, but the factors of time, space, and communications have taken on new dimensions with the result that problems can generate like lightning and can spring full-grown, in great numbers, from the dragon's teeth of today's rapidly shifting social and economic pressures. In this welter of pressing and important factors, it is difficult indeed to select the wisest policy and to forge the best tools for the implementation of policy. Such being the case, before there can be any truly sound evaluation of the role of sea power in the future, there must be an objective overall appraisal.

A comprehensive estimate of the situation would include a scrutiny of the forces at work in the world, the political and sympathetic alignments of powers, the validity and substance of racial and group aspirations, and a facing up to the actuality of the imbalances of various sorts which exist or appear to be developing. In this day and age, importance attaches not only to obvious threats to worldwide peace but also to threats against the peace in important local areas—and no area seems to be unimportant today. Thus, ambitions and hopes are assessed in the light of the probabilities and threats of the future. Future history will be shaped in great measure by the steps which are taken as a result of these appraisals and reappraisals. If we are wise and resolute, we will retain a measure of volition with respect to the history of the future. There are many areas in which we must move wisely, and sea power is one of them. You may be sure that our own history, and the history of the world, will be profoundly affected by the effectiveness of our maritime strength and our fortunes at sea.

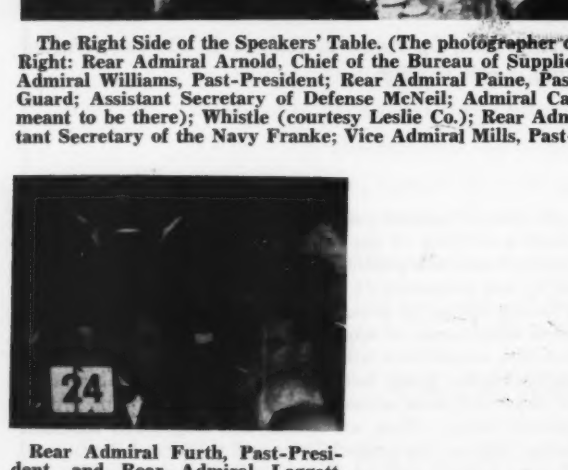
If the forecast presents acute problems—which it undoubtedly does—there are many things which the nation must be prepared to do successfully to meet the expected dangers and emergencies of the future. These measures encompass the fields of economic and financial strength, the political field with its many interlocking factors, the great and pressing nationalistic and sociological movements of our times, and the matter of military posture.

Pinpointing the military aspect of the problem, while recognizing that it is, after all, only one of the important elements of national strength, I believe it could safely be said that in this age the principal objectives of the military structures are:

The Right Side of the Speakers' Table. (The photographer could find no proper spot from which to get the Left Side). Left to Right: Rear Admiral Arnold, Chief of the Bureau of Supplies and Accounts; Rear Admiral Lonnquest, Past-President; Rear Admiral Williams, Past-President; Rear Admiral Paine, Past-President; Vice Admiral Richmond, Commandant of the Coast Guard; Assistant Secretary of Defense McNeil; Admiral Carney, Principal Speaker; the Secretary-Treasurer (who was not meant to be there); Whistle (courtesy Leslie Co.); Rear Admiral Cowart, Presiding; Rear Admiral Mumma, Toastmaster; Assistant Secretary of the Navy Franke; Vice Admiral Mills, Past-President.

Rear Admiral Furth, Past-President, and Rear Admiral Leggett, Past-President. The Society's two most recent Past-Presidents who were not at the Speaker's Table.

President Cowart welcomes members and guests to the Annual Banquet.



Assistant Secretary of Defense McNeil flanked by Admiral Carney on his left and the Commandant of the Coast Guard on his right.

1. To protect the vitals of the United States against disastrous surprise attack;
2. To maintain the ability to retaliate swiftly and fearsomely in the event of attack;
3. To maintain an ability to carry on a sustained and diversified effort.

Protecting our own vitals and being able effectively to retaliate must in these days be considered as cornerstones of military thinking, but there are other factors which are also of vital importance and which must not be relegated to the background by the more dramatic need for continental defense and retaliatory capability.

In contemplating any military struggle of the future, two general situations must be postulated; atomic war, and non-atomic war. It can be argued—and earnestly hoped—that the horrors of a full-scale atomic exchange would be such that even the most perverted human intelligence would shy away from invoking it. Nevertheless, we cannot forget that we have been shocked and disillusioned by brutality and callousness in our own lifetime and, therefore, it is only prudent to be ready to defend ourselves under any contingency, even including atomic war. On the other hand common sense, or perhaps fear, may stay the hand that could release atomic attack; in such circumstances, should a lesser struggle be triggered, again it is the part of prudence to be prepared successfully to win.

Let us first look at the possibilities of atomic war. In its simplest form we could say that such a struggle could be divided into two phases. The first would be violent and perhaps could be critical; if human toughness could weather such an onslaught, the second phase would be a campaign of attrition and endurance. In the first phase, the basic problems would be the interception and blunting of enemy attack, the retaliation, and the measures aimed at minimizing the paralyzing effect of attack. Even in such a blitz, with its overriding accent on the air as the avenue of attack and the initial battleground, the sea would be an important extension of our ramparts and one more springboard for counterattack. The second phase of atomic war—attrition and endurance—would surely involve the familiar old pattern of struggle for the sea.

The pattern of non-atomic war would be familiar insofar as operations are concerned, although the composition and capabilities of the forces would differ radically from those that brought World War II to a successful military conclusion. The military struggle would be waged with modern refinements of what we are pleased to call conventional weapons, but it would also be prudently necessary for us to maintain, *in being*, adequate atomic forces for their deterrent effect—and as necessary insurance in the event deterrence failed.

In any war that I can visualize, endurance and a surviving industrial potential would still be powerful factors and, for us to realize our full potential, the sea lanes must be recognized as vital and we must have, ready at hand, forces to keep them open for our own purposes and denied to any enemy. Were we to be blitzed, the seas must bar any hostile exploiting follow-up. If we were forced to pick ourselves up from wreckage to fight on—as I believe we would—control of the seas would be a prerequisite to such victory as could be salvaged.

In any non-atomic struggle of the future, loss of control of the sea would surely spell defeat and, here again, there is obvious need to have, ready at hand, maritime forces which would enable us to push through to our own objectives at the same time defeating any and all enemy efforts to disrupt our movements at sea.

Assuming the possibility of either atomic or non-atomic struggle, our security forces must be able to cope with both situations—and must have the requisite offensive and defensive characteristics to stave off defeat and press on to victorious solution in either of those eventualities.

There must be adequate dispersal of forces and their supporting elements to minimize atomic damage. There must be a capability for atomic attack and a comparable capability for atomic defense. The same is true with respect to the assumption of non-atomic conflict; our forces must be able to withstand any initial shock, must be able to fend off enemy efforts, and must have the capability of striking the necessary blows to win a decisive outcome.

Rapid advances in technology, on both sides of the Iron Curtain, pose a terrific problem to science, industry, and the military. Speed alone has introduced compressed time elements which make difficult or impossible many defensive solutions if depending on manual methods; in many instances, the rapidity of development of the tactical problem is such as to defy assimilation and coordination of man's mind alone. Offensively, the mechanical brains of weapons must solve intricate flight and target problems and must circumvent enemy counter-measures to prevent being thrown off the track. Our forces and weapons must be able to penetrate enemy defenses and defeat enemy attacks; the accomplishment of these objectives, today, is taxing our scientific and technical skills, and our production capability, to the utmost.

Participation by Naval forces, under their assigned roles and missions, in a super-blitz type of struggle calls for both offensive and defensive capabilities over the sea, on the sea, and under the sea. The forces and their weapons will be tailored to the targets which they must strike and to the threats which they may encounter. Navies do not think only in terms of meeting other navies, nor can armies and air forces confine their thinking to enemy counterparts; each of the Services has obligations to cooperate with the others and to make contributions toward the achievement of the objectives of sister Services. Offensively, the Navy must support the efforts of the Air Force and work to the end that our ground forces may project their power from secured beachheads and areas; these in addition to the offensive roles assigned primarily to the Navy. Defensively, the Navy must man the sea ramparts and make its contribution to detection, interception, and tracking of threats to our shores, whether they move by sea, by air, or from under the sea. Also, of course, our maritime forces must be able to protect themselves against specific attack.

All of these requirements dictate the creating and maintaining of a powerful and versatile Navy capable, in conjunction with allied forces and our own sister Services, of insuring that degree of control of the sea which is necessary. Every technological advance which can be incorporated to advantage into the characteristics of ships and planes and weapons must be sought. The picture is even now unfolding; the Fleet is evolving into a powerful family of ships and planes whose capabilities will be vastly enhanced by the introduction of nuclear power; the range, accuracy, and lethal potency of weapons are being continually extended by the operational application of scientific and engineering advances; and the brains of science are producing electronic brains for

the instantaneous solutions of problems too complex for quick handling by the mind of mere man.

The times in which we live have been variously referred to as the air age or the nuclear age. Perhaps it would be more accurate to say that we are living in an age of practically applied advanced science. True, the capabilities of aerial operations are constantly increasing, and it is equally true that the introduction of the atom is having a profound effect on our lives and on our imaginations. From the standpoint of sea power, all of those catch phrases are meaningful. Piloted and pilotless vehicles are profoundly affecting the business of maintaining control of the sea. Mass air transport by giant planes, as yet only in the minds of the imaginative, may by-pass some of the dangers of the sea and absolve the maritime forces from some of their surface burdens. There are concepts of aerial logistic support of sea-going forces which, when feasible in terms of available aircraft, will profoundly affect the endurance and the capabilities of our sea forces. The entire complexion and capabilities of our sea forces could be revolutionized by the general availability of nuclear power to ships and planes. An increase in the family of healthy and diversified missiles may not cause the disappearance of the gun, the torpedo, and the bomb in our day, but the lethal range of the new weapons will be greatly extended beyond the capabilities now known.

With a little imagination, and even an elementary understanding of the things that are coming to pass, one can conjure up a reasonably good picture of the ships and planes and weapons of the future as they evolve from today's prototypes. But one thing will not change: people. If we think of the "Navy of the future" totally in terms of material things, we could be beguiled into neglecting the one ingredient which will be essential in the atomic fleet just as it was in John Paul Jones' day . . . "People"—knowledgeable people, loyal people, resolute people, and disciplined people. Contrary to the earlier predictions of some, the demand for human ability and a high order of character and leadership is increased with the advent of the push-button. Whatever the "Navy of the future" may look like, its inner worth will be measured by the caliber of its people. They will have the privilege of playing an important role in history—a great and successful role as long as our country realizes that there is no substitute for power at sea in the scheme of our national security. Other elements of power are also essential, but none is a replacement or substitute for sea power.

Just as surely as sea power played a leading role in the outcome of the past, so will it exert a powerful influence on the shaping of affairs of the future. New factors of time and space, new dimensions of destruction, have come upon the scene; new stirrings and new fears are affecting men's thinking; theories are being sorely tested by the realities of survival—many, many influences will be brought to bear on the peoples of the world. Spectacular, dramatic, and urgent matters will compete for man's attention, perhaps at times overshadowing the inexorable but more gradual maritime pressures. Nevertheless, nothing we may do can prevent our ultimate isolation, our fading from greatness, our loss of worthy leadership—possibly our defeat—if we fail to retain our mastery of the essential arteries and areas of the seas. Nothing we do can hold the confidence of allies, if our communications by sea are severed. The best efforts of statesmen, industrialists, scientists, and our sister Services would go for little should we and our allies and friends become hemmed in and separated by hostile oceans.

Therefore, there can be no other conclusion but that the measure of our Naval preparedness will have much to do with what future history has to say about the part which the United States has played in the great quest for a decent and honorable peace. This is one of the fields in which we have the opportunity to shape a bit of history. Today our pre-eminence at sea is being challenged; we must meet that challenge for, if we fail to do so, history will surely record the decline of the United States as a great and potent champion of freedom—and may well mark the decline of freedom itself.

CAPTAIN ROBERT T. SUTHERLAND, JR., U. S. Navy, Retired

# *THE WEAKEST LINK, SHIP AUXILIARY PROPULSION*

**THE AUTHOR**

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## EXPOSITION OF A PROBLEM

A "balanced design," adapted to meeting both general and specific requirements, is the aim of every competent naval architect and marine engineer engaged in the design of a merchant or naval ship. At every stage of the project he reconciles conflicting demands of speed, useful carrying capacity, adequacy of accommodations, radius of action, strength, size and cost, and finally must produce a compromise acceptable to both his own principles and his principals.

Almost inevitably, in the interest of putting the ship into early service, and because of limitations of cost, unavailability of desired materials or components, possible shortsightedness or ignorance, inadequate specifications, and other reasons, the degree of balance actually achieved, though generally acceptable, leaves something to be desired.

Owners, operators, designers and insurers all attempt to foresee the casualties that may occur in service. They try to evaluate their relative seriousness and make provision for avoiding or overcoming them as well as can be within the limitations of the design. Shipboard allowances of stores are established and filled. Ship and shore-based spare parts are purchased and distributed. Emergency communication and lighting systems are provided. Safety of life at sea equipment is furnished. Standby and emergency fuel, lubricating oil and water pumps are usually installed. In naval ships, alternate methods of steering, secondary means of gunfire control and seemingly large amounts of damage control equipment may be provided. Expensive separation of boilers, engines and auxiliary machinery into a number of isolated watertight compartments complicates operation but offers compensatory advantages such as greater flexibility in selection of propulsion machinery in operation at any time and improved resistance to damage.

After painstaking study, self-contained means may be provided for overcoming trivial annoying situations most unlikely to ever occur. Simultaneously, the selfsame well-meaning people usually make no provision against the smaller odds that the ship during her service life will lose or damage her rudder, tailshaft or propeller, or for other reason, such as flooding of machinery spaces, become exposed to the greater dangers inherent in a relatively long-term loss of propulsive power and control. Certainly such a design cannot be considered effectively balanced from a probability point of view. Unfortunately, precisely that situation is the case as regards substantially all single-screw ships. Multiple screw ships are generally less vulnerable although in time of war a single mine, bomb or torpedo might instantaneously rob the ship of all means of applying propulsive power, whether or not engine or other compartments were damaged.

Ever since the adoption of the screw propeller, each year significant numbers of ships have experienced sudden loss of steering control or propulsive power because of damage to rudder, propeller, or main engines. In a harbor or other restricted waters further more severe damage, sometimes amounting

to total loss, may ensue to the ship herself or to other ships or structures with which she may collide before control of the situation is regained. Should unfavorable conditions prevail, extensive loss of life may be a sequel to the casualty.

When damage has been sustained at sea which the crew is unable to promptly overcome, and propulsive power or control has been lost for an unavoidable period of time, a potentially dangerous and costly situation exists. Assuming an intact hull following the casualty, fine weather, calm seas, plenty of searoom, and tug service available from not too great distance, the situation is not desperate. Even so, several days may be spent wallowing around before a tug has reached the scene, passed her towline, taken the disabled ship under tow and completed the trip to the nearest repair facility. Very substantial costs will be incurred for tug service, purchase of replacement materials or parts and delivery to the repair activity engaged, emergency or permanent repairs, loss of perishable cargo, loss of earnings of the ship, wages and hotel costs of crew, disposition of passengers, etc. Those costs might be very much reduced if by the employment of auxiliary propulsion the ship were enabled to proceed at reduced speed after the casualty and discharge her cargo, passengers and crew. She could subsequently enter a selected repair yard at a time when it was in all respects ready for her and the necessary materials had been preassembled for rapid accomplishment of complete repairs.

The dangers of the situation are compounded when an approaching storm, rough seas, a lee shore, limited visibility, the distance from tugs, progressive flooding with its possibility of sinking, severed communications, severe structural damage, or other complications exist or threaten. Should loss of propulsive power or steering unhappily occur during wartime in enemy infested waters, odds against saving the ship, her cargo, passengers and crew skyrocket.

A ship experiencing such a casualty while cruising in convoy or other formation is a possible hazard to all ships in the group. Often, such other ships must maneuver to avoid and assist her. Escorts must be provided at least until personnel can be removed and disposal made of the damaged ship, at the risk of loss of life and damage or loss of the escorts. If, as has been the case with some combatant ships, it is decided to take the cripple under tow to a repair facility, make temporary repairs and subsequently by further slow towing, return her to a safe area for permanent repair and eventual restoration to service, the costs may far exceed the actual worth of the ship. It is questionable whether the intangible gain in morale at home, plus the real material gain, together justify the enormous costs in manpower, money, loss of services, and the risks undergone by accompanying vessels, even if the operation be completely successful. However, when the damaged ship, or remaining half ship, can get underway and proceed to port or a safer area on her own, using a self-contained means of auxiliary propulsion, everyone must admire and applaud her performance. Sometimes but a few miles need be traversed, even while sinking, to reach a safe beaching area, or while awaiting the arrival of air cover, daylight, the breaking off of action, or to speed contact with rescue units.

An auxiliary means of propulsion and steering would be of obvious advantage in moving a "dead ship" without the necessity of employing tug service. With ship and tugboat crews on strike, the ability of limited numbers of non-striking personnel to move the ship short distances may be important in order to provide berths where other incoming vessels may be discharged, loaded, or safely secured while the strike persists. No one can fairly dispute the operator's right to safeguard his investment by moving his ship away from a fire on the pier alongside or to a safe anchorage in the face of a threatening storm. Every well-managed union favors preservation of plant and jobs to return to after agreement to end the strike has been reached. But, despite willingness of union leadership and members to preserve the normal sources of their income, sufficient striking personnel may not be near at hand to cope with an emergency situation and time may be of the essence.

It must be agreed that there is demonstrable need for auxiliary propulsion and steering although divergent views may persist as regards the importance of the problem. While it may be argued that possible losses are partially recoverable if adequate insurance coverage has been maintained, insurance alone is rarely a completely satisfactory solution to the problem. Anyhow, like others, insurers are in business to make a profit. Insofar as experience and judgment indicate, they will charge sufficiently high premiums to more than cover the risks incurred. Just as a prudent sailor habitually carries oars in a sailboat, even though it and his life be fully insured, an alternate means of propulsion should be provided for every larger ship.

### ELEMENTS OF AN ACCEPTABLE SOLUTION

If there is tentative, reserved agreement that a problem exists, a logical next step would be to determine and more sharply define the essentials of an acceptable solution. Whenever existence of a problem or need has been fully established and its nature explored, specifications leading to a solution may be developed. The hardest part of the job of solving the problem has then been completed. Generally, personnel of nearer average capabilities can successfully "carry-on" from that point, once guideposts and limits for their activities have been established.

Assuming, for the present, that auxiliary propulsive and steering power *could* be provided, at a cost, it is of interest to estimate *how much* auxiliary power merits serious consideration. Certainly duplication of the amount of main power is an unacceptable answer, for the ship might well end up carrying little more than engines and the crew to man them. Here for once, the well-known extremely disproportionate increase in power required to obtain small increments in speed is in a sense advantageous and serves our purpose.

Though great shaft horsepower is required for a given ship to reach her designed speed, trial board reports consistently confirm that only about one-eighth as much is needed for half speed. Less than a thousand shaft horsepower will propel a 12,000 displacement ton C-3 at 10 knots; two hundred fifty horsepower will suffice for a loaded 14,000 displacement ton Liberty ship at 6 knots; two hundred SHP will move a 1,600 ton destroyer at 8 knots; a mere seventeen SHP is enough to drive a fully submerged 2,400 ton submarine at 2 knots.

In estimating power requirements of a ship, use is often made of the empirical formula

$$SHP = \Delta^{\frac{2}{3}} V^3 / c \qquad (1)$$

where

SHP represents shaft horsepower,
$\Delta$ represents displacement of the ship, in long tons,
c is the so-called "Admiralty coefficient," and
V is the speed in knots.

The Admiralty coefficient is not constant. On the contrary, for a particular ship (except in the case of very high speed naval ships) the coefficient generally becomes smaller with increasing speed.

If, for present purposes, the relatively unimportant but conservative assumption is made that the Admiralty coefficient of a given ship remains constant with decrease in speed (i.e. as the speed-length ratio $V/\sqrt{L}$ decreases), instead of increasing as suggested above, the familiar "rule of thumb" is developed; power required varies as the cube of the speed.

$$\frac{shp_1}{SHP} = \frac{\Delta^{\frac{2}{3}} v_1^3}{c_1} \times \frac{c}{\Delta^{\frac{2}{3}} V^3}$$

When $c_1$ is assumed to be equal to c,

$$\frac{shp_1}{SHP} = \left(\frac{v_1}{V}\right)^3 \qquad (2)$$

where

$shp_1$ = estimated shaft horsepower at a reduced speed,
SHP = actual full power shaft horsepower,
$v_1$ = reduced speed, and
V = full speed.

A semi-logarithmic plot of equation (2) is reproduced as Figure 1. The relatively insignificant amount of power required for slow-speed operation is clearly shown. To demonstrate that the "rule of thumb" is not grossly in error, actual trial board data for three ships have also been plotted. For the representative ships selected, the "rule of thumb" overstates power requirements for all except two of approximately forty points for which trial data were available.

Trial board data for three merchant ships and one obsolete destroyer design are plotted in Figure 2 in terms of actually measured shaft horsepower corresponding to speed in knots on a measured mile, the speed having been corrected for the effects of tide and wind prevailing at the time of trial. Again, for clarity in the lower speed range particularly, the plot is semi-logarithmic. Data have not been reported (and

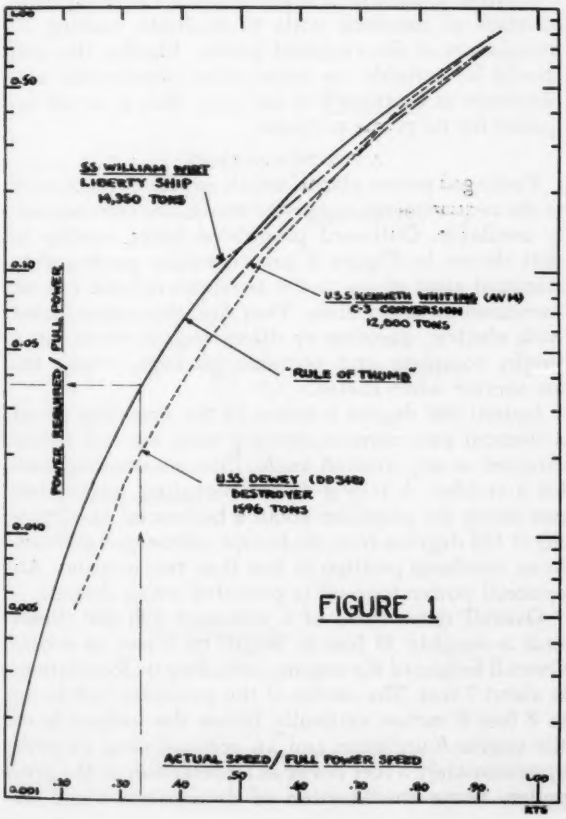



FIGURE 1

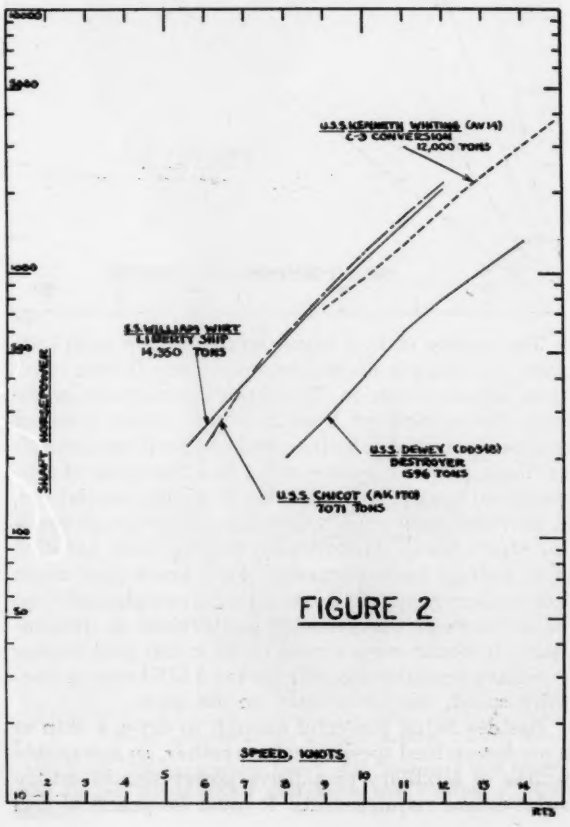



FIGURE 2

perhaps were not obtained) for speeds below those shown. Extrapolation would indicate further reduction in power required at slower speeds.

If there is guarded acceptance of Equation (2), on a linear plot of main engine shaft horsepower provided in the ship versus approximate substitute auxiliary shaft horsepower which would be required, it is possible to draw lines for one-fourth, one-third, forty per cent and half speed—indeed, for any percentage of full speed which may be of interest. In making such a plot, there is an assumption that the auxiliary power can be applied equally as efficiently as the main power.

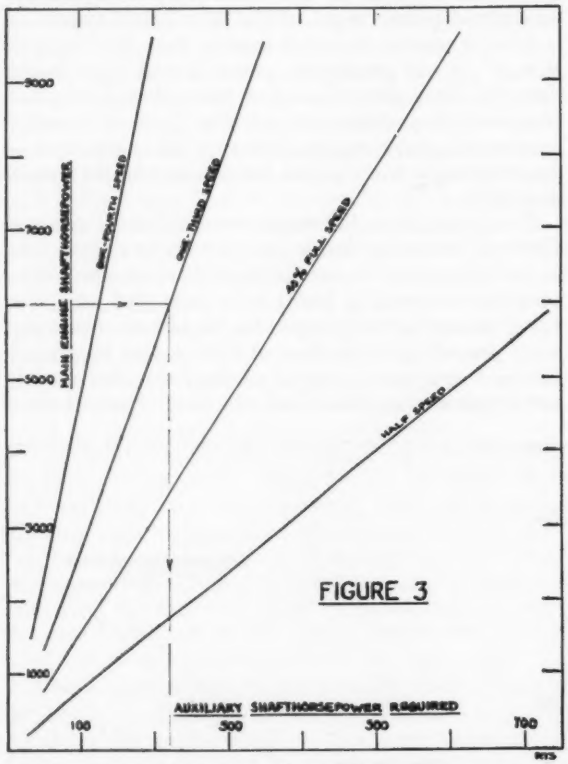



FIGURE 3

The matter of *how much* auxiliary power to consider providing is dependent upon many factors other than personal opinion. The capital investment in the ship, the number of lives involved, routes traveled and recognizable risks incurred are pertinent considerations, just as they are in the determination of conventional insurance premiums. Auxiliary propulsion, if provided at all must, to be of use, give enough speed for steerageway. Historically, having been satisfied with average towing speeds of 4 to 7 knots (and much lower average speeds if computed on an elapsed-time basis between the casualty and arrival at destination), it would seem a reasonable initial goal to plan auxiliary propulsive power for say 5 to 6 knots or one-third speed, whichever may be the least.

Besides being powerful enough to drive a ship at a predetermined speed in calm weather, an acceptable source of auxiliary propulsive power should satisfy subordinate requirements. It must be practical and available if it is to meet the legendary tests of "will it work?" and "can it be made?" Preferably, it should be semi-portable in order that the auxiliary might, in an emergency, be relocated in a given ship or even moved from ship to ship. It should be self-contained in all respects except fuel. The type of fuel required should be safe for carriage and normally available in quantity on the ship to which the auxiliary propulsive unit is furnished. The unit should be adaptable to "jerry rigs" and should not presuppose a college education for maintenance, installation or operation.

Other desirable characteristics of an auxiliary propulsive unit would include a built-in means of controlling the direction of thrust in order that auxiliary steering might be incorporated in the same power package. Only minimum amounts of maintenance should be necessary for the large percentage of the time that the unit is in a standby condition, and it should be possible to accomplish that limited maintenance without special arrangements and equipment. The unit should have proven reliability with low susceptibility to damage whether or not in operation. It should be built for heavy-duty service, capable of continuous operation at reasonable efficiency for extended (but nevertheless limited) periods of time. Optional remote or local control would be desirable.

Like every other component of a good ship design, the unit should make minimum demands on space and weight and should be reasonable in cost. It should either be obtainable in graduated sizes suitable for individual applications or be designed for ready combination of standard units to facilitate making an installation of the required power. Ideally, the unit should be suitable for some other worthwhile employment at least part of the time that it is not required for its prime purpose.

### A POSSIBLE ANSWER

Packaged power plants, which appear to meet most of the requirements suggested above, are commercially available. Outboard propulsion units, similar to that shown in Figure 5, are currently produced in standard sizes of up to 400 horsepower, and can be furnished in larger sizes. They are obtainable, fitted with electric, gasoline or diesel engine drive, as a single, complete and portable package, ready for for service when fueled.

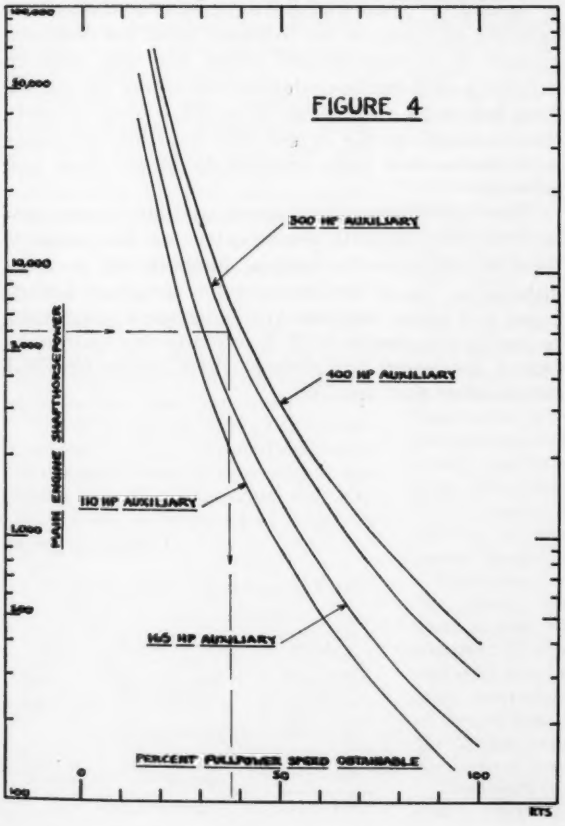
Instant 360 degree rotation of the propeller about a vertical axis permits steering with the full thrust directed at any desired angle, thus eliminating need for a rudder. A power-driven elevating mechanism can swing the propeller about a horizontal axis, raising it 180 degrees from its lowest submerged position to an overhead position in less than two minutes. An optional power take-off is provided when desired.

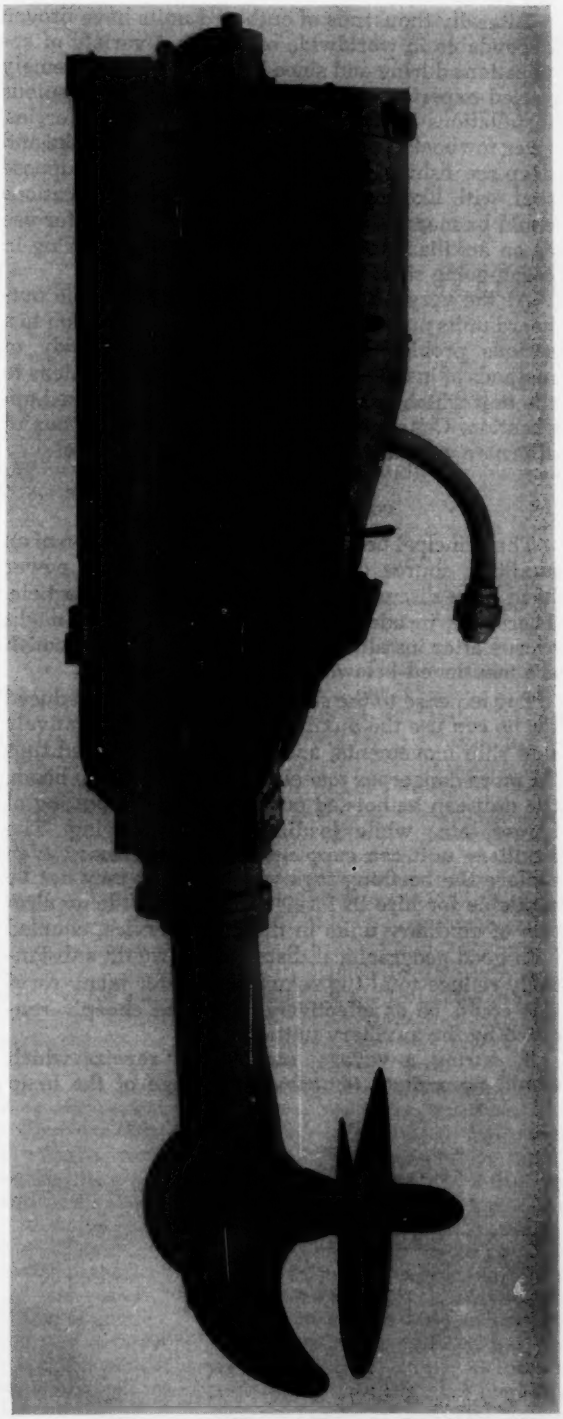
Overall dimensions of a standard 300 HP diesel unit is roughly 14 feet in length by 5 feet in width. Overall height of the engine, including its foundation, is about 7 feet. The center of the propeller hub is up to 8 feet 6 inches vertically below the underside of the engine foundation and an optional skeg extends approximately 3 feet lower as a protection to the propeller. Some modification of dimensions could be

made to suit particular requirements. Dry weight of the standard complete 300 HP unit is 9 tons. Standard towing propellers are fitted. Those for the most powerful standard units have diameters of 66 inches to 88 inches, pitch of 50 inches to 68 inches, and are geared to deliver full power at about 275 revolutions per minute. Operational periods between overhauls of up to 45,000 hours at rated power are not uncommon. If shorter intervals between routine overhauls are acceptable, as would certainly appear appropriate for the proposed auxiliary application, substantial reductions can be made in weight, cost and dimensions.

In the case of a ship with high freeboard, design provisions could be made to permit installation of the unit at a level low enough for proper propeller immersion or, if preferred, the engine and outboard drive can be separated and installed in different locations. Relatively simple provisions for emergency over-the-side installation, in one or more locations, are practical provided that partial or complete waterproofing of the engine is accomplished. In some cases, semi-permanent installation of the unit might be made on a platform deck aft, permitting the outboard drive to be located outside of the stern plating. When not in use, the propeller and drive would be stowed in an elevated position, with the propeller at or above the main deck level.

Again using the "rule of thumb" earlier mentioned, it is possible to show in Figure 4, another semi-logarithmic plot, the percentage of full-power speed to be expected when using one of four standard outboard units for the propulsion of a ship which at full



(Photo courtesy Murray & Tregurtha, Inc., Quincy, Mass.)

**Figure 5. 225 horsepower heavy-duty outboard unit adaptable to use for auxiliary propulsion and steering of large ships.**

power develops known shaft horsepower. The plot assumes equally efficient application of the power in the two cases.

Literally thousands of outboard units have proven dependable in worldwide service in a variety of applications during and since World War II. Extremely varied experience has been obtained with ingenious installations in landing barges, lighters, car ferries, river towboats, harbor and coastal tugs, and lake and deep-sea fishing boats. There is reason to suppose that, with like ingenuity, any essential modifications could be made to the unit to make it suitable for use as an auxiliary means of propulsion and steering in ocean-going ships of conventional form.

At the very least, the availability of reliable outboard units puts the finger on a potential solution to a serious problem and should encourage study of methods of installation and the possible alterations to the unit which would best fit it for the proposed application. Concurrently, of course, investigations of alternate competitive solutions might be made.

### CONTINGENT BENEFITS

The principal benefits obtainable by provision of an auxiliary source of propulsion and steering power have been discussed in earlier parts of this article. There are, in addition, fringe benefits which might accrue after installing auxiliary units, some of which are mentioned below.

Tug expense to the ship operator could be reduced for he can use the auxiliary unit alone for relatively safe ship movements, and to supplement hired tugs for more dangerous maneuvers. Using a cargo boom, the unit can be hoisted out and used for spotting of barges, etc., while loading and discharging. The auxiliary unit can supplement or if necessary even replace the berthing tugs which may or may not be available for hire in foreign outports. Wide application of auxiliary units in the naval service, coupled with good geographical distribution, would substantially reduce total tug requirements, for many services could be as effectively and more cheaply rendered by the auxiliary unit.

If, during a voyage, engineroom repairs which would necessitate temporary stoppage of the main engines become desirable, they may be accomplished without too serious effect on the ship's schedule and before more serious damage is done, by simply cutting-in the auxiliary unit and proceeding at reduced speed until the main plant is again in operation. Urgent repairs can be made under circumstances and in areas where a prudent Master would not dare be completely without power and steering for even short periods of time.

In other ways, the mere presence of an auxiliary unit can lend comfort and a sense of safety to officers and crew, as when traversing a canal or restricted waterway, when sharp turns may be required under adverse weather conditions, to relieve the strain on a chain cable if needed, or to supplement worn lines when berthed in a tideway. Particularly in the case of a single-screw ship, the auxiliary can materially expedite maneuvers and perhaps save much time in a tight schedule.

Availability of an emergency means of propulsion could be used as an argument for reduced insurance premiums. Or, if one cared to go so far, as a reason for accepting reduced margins of safety in certain elements of a main propulsion plant, in order to enjoy attendant reductions in cost, weight and space. Elimination of certain shipboard spares might be appropriate, with consequent reduction in investment required, making minor increments in space and weight available for other purposes.

If an emergency should arise necessitating getting a "dead ship" underway and out of port at the earliest possible moment, as for instance upon the close approach of an unpredicted storm, the ship with an auxiliary unit can be underway and out of the harbor long before its main steam propulsion plant is safely "warmed up" to the extent that the Chief Engineer and Master are both satisfied to let-go lines and proceed.

More subsidiary advantage of auxiliary propulsion and steering could be enumerated, as, for instance, possible reduction in tactical diameter of an antisubmarine vessel. However, if the *principal* advantages and safety features are considered insufficient to justify consideration, it is unlikely that any number of *incidental* advantages which might be cited would alter that opinion.

# *NUCLEAR POWER FOR COMMERCIAL SHIPS*

**ACKNOWLEDGEMENT**

*This is an abridged version of a paper presented by K. Maddocks, Assistant Professor of Marine Engineering, University of Michigan, at the Institute of Marine Engineers on 20 December, 1955. It is reprinted from the January, 1956, edition of "The British Motor Ship," with certain additional information from the December 23, 1955, edition of "Engineering."*

SINCE the presentation of Sir John Cockcroft's paper (1) on the subject in 1953, much information has been released on the subject of power production using nuclear fuels and it seems pertinent that a survey should be made to define how this evolution in technology may affect the professional marine engineer.

Probably one, and possibly two, nuclear-powered merchant ships will be in operation within the next five years. These will not be competitive in either first cost or operational cost with vessels propelled by orthodox machinery, primarily because of the inevitable expense attached to the development of any new type of machinery. However, outside of this factor, it is hoped to show that the balance will not be as unfavorable to the nuclear-powered plant as has been suggested.

The U.S. Atomic Energy Commission has recently prepared estimates of the economically recoverable reserves of both conventional and nuclear fuels, an abstract of which is given in Table I.

TABLE I—*World Reserves of Fuel*

| Fuel | World Reserves | Energy in B.T.U. |
|---|---|---|
| Coal..... | $3,482 \times 10^9$, tons | $72.2 \times 10^{18}$ |
| Oil..... | $186 \times 10^9$, tons | $7.6 \times 10^{18}$ |
| Gas..... | $560 \times 10^{12}$, cu. ft. | $0.6 \times 10^{18}$ |
| | Total Conventional | $80.4 \times 10^{18}$ |
| Uranium. | $25 \times 10^6$, tons | $1,700 \times 10^{18}$ |
| Thorium. | $1 \times 10^9$, tons | $71 \times 10^{18}$ |
| | Total Nuclear | $1,771 \times 10^{18}$ |

The details released in the recent White Paper covering Britain's 10-year plan for nuclear-power development convey a note of optimism despite the capital cost involved. The White Paper states that the fuel supply prospects are now better than previously anticipated. Considerable deposits of medium- and low-grade uranium ores are known and thorium has distinct possibilities for conversion to a nuclear fuel. The Government is confident that the necessary supplies will be available when required. In dealing with an installed capacity of eight power stations in excess of 1,000 megawatts, this White Paper concludes, "This formidable task must be tackled with vigor and imagination. The stakes are high, but the final reward will be immeasurable."

Several excellent texts (2, 3, 4) have been published on the principles and applications of the new technology and to include a similar complete treatment is outside the scope of this paper. However, in the interests of continuity, the following points should be borne in mind.

Fissioning is the splitting apart of the atomic nuclei of the material used as fuel. The addition of another neutron to the nucleus of a fissile material is sufficient to cause an agitated state and subsequently split up of the nucleus. The kinetic energy of the fission fragments is dissipated in the form of heat and other radiation.

Theoretically, one pound of nuclear fuel, which has a volume slightly in excess of one cubic inch, if completely fissioned, releases energy equivalent to $43 \times 10^9$ B.T.U. or approximately 1,000 tons of fuel oil.

All reactors to date have been designed to use either Uranium 235, Uranium 233 or Plutonium 239 as fuel. Thorium 232 is a fertile material, which can be converted to a fissile material in a breeder-type reactor. (The numbers indicate the atomic weight or the sum of the neutrons and protons in the nucleus of the atom of that material.)

Natural uranium, U.238, contains only 0.7% U.235 by weight; the other two fuels, U.233 and Pu.239, must be produced artificially. The degree of enrichment of the fuel is the proportion of fissile U.235 to non-fissile U.238. The higher the enrichment, the more efficient "burn-up" of the fissionable U.235 can be expected.

### TYPES OF NUCLEAR REACTORS

Reactors are classed as either "thermal," "intermediate" or "fast," depending on the energy level of the neutrons. In a "thermal" reactor, the neutrons are slowed down considerably by a moderator before continuing the fission chain reaction. When the moderating action allows a higher neutron energy level to operate, the reactor is said to be of the "intermediate" type. If no moderator is provided to slow down the neutrons, then the reactor is "fast" and in some cases a fuel diluent may be necessary to spread the nuclei and so decrease the thermal flux density.

The form of the fuel, coolant and

moderator create further classifications. In a homogeneous reactor, the fuel, coolant and moderator (if used) are mixed, often in liquid form. In a heterogeneous reactor, these are separated usually in solid form, which allows a definite geometric arrangement, e.g., round rods of fuel can be slipped into the moderator block in much the same way as marking pegs are placed into a cribbage scoreboard.

A reactor is said to be regenerative if it replaces all or part of the fissioned (burned up) fuel by creating new fuel from non-fissionable fertile material. If this replacement is equal to the amount of fuel consumed plus some excess, then the reactor is known as a breeder.

Other distinguishing characteristics are the enrichment and type of fuel, the coolant used, and, for the thermal reactor, the moderator used. A complete discussion on the recommended materials to fulfil each of these functions is given in reference 5.

### OPERATION OF A NUCLEAR REACTOR

The reactor is said to be critical if at least one of the neutrons (two or three are produced with each fission) is available to split up another nucleus and thereby maintain the chain reaction. This neutron multiplication factor (usually denoted by "k") therefore determines whether the reactor is critical or not. If the value of "k" is unity or above then the reactor is critical, but if the value falls below unity, the reactor becomes subcritical and the chain reaction ceases.

As a fissile fuel has the property of continuously emitting neutrons, some means of adjusting the "k" value is required to prevent a spontaneous build-up to criticality. This is provided by control devices which have a high capacity to absorb neutrons. In the heterogeneous reactor, these devices are usually in the form of rods and shims of either cadmium, cobalt, hafnium or boron steel alloys. The movement of the rods gives a coarse control and the shims a fine control of the neutrons. In the "cold" position, both rods and shims would be full in. The power level of the reactor is selected by the withdrawal of the rods a predetermined amount. Then the gradual withdrawal of the shims further increases the "k" value of the reactor until it becomes critical and the system gets under way.

Since operating personnel would normally be located in a control room (6) without access to the "hot" reactor, the various operating factors such as control rod position, strength of neutron flux and coolant flow, etc., must be measured and transmitted to the control room by various instruments. These individual signals must then be used to operate automatically the reactor in a stable condition at the power level required.

Possible radiation hazards in the form of gamma rays or escaping neutrons must be detected by an elaborate system of sensing instruments located both inside and outside the reactor. The marine installation would also require these instruments on the ship's hull and on the ventilating system and sanitary system. The removal of the spent fuel and its replacement by new fuel requires the use of remote controlled handling gear.

The waste will remain radioactive for a considerable period and two methods have been used for its disposal. One is to bury it in a concrete vault in as remote a location as possible. The other is to encase it in concrete and dump this out at sea. This is certainly not a commodity that can be kicked around until it is lost.

### SELECTION OF REACTOR TYPE FOR MARINE USE

It will be appreciated that, by various combinations of the characteristics outlined above, the number of "possibilities" is very great.

Fortunately, this range can be narrowed considerably by space and weight considerations and also from the fact that a plant capable of producing replacement fuel is precluded. Such a breeder reactor would require a far too extensive ancillary chemical plant and shielded material handling equipment to be accommodated on shipboard. To exploit fully the main advantage in reduction of fuel weight and to offset as far as possible the expected high first cost and fuel cost, a minimum of 15,000 s.h.p. is indicated.

The present monopoly of the steam turbine in this range of power, with the consequent accumulation of design and operating technique, has no doubt influenced the choice of steam as the working medium. It has, in fact, been stated frequently that the only difference between a nuclear fueled steam plant and a fossil fueled steam plant is the type of boiler used. That this is an over-simplification will be seen from the discussion of some of the possible reactor designs which follow. Also, the operational control of the fluid conditioning unit (reactor) and the turbine must be more closely integrated than is the case even with advanced steam plants using automatic combustion controls.

A list of feasible types of reactor, with no implication of the order of precedence, becomes:—

1. Pressurized water reactor.
2. Boiling water reactor.
3. Homogeneous reactor.
4. Sodium loop reactor.
5. Gas-cooled reactor.

This list was computed from study of the U.S. Atomic Energy Commission's published five-year plan in which an investment of $200 million will be made in developing five separate types of power reactors. It is anticipated that this plan will bring within sight the objective of harnessing nuclear power on a basis economically competitive with coal and oil. The first four reactors are versions of those included in the United States A.E.C. plan. The fifth will use a closed-cycle gas turbine as a power-producing unit, operating with helium as a working fluid.

The characteristics of each reactor design will now be considered. The illustrations should be read liberally. Detail design of a particular reactor depends on the type of vessel in which it is to be used. For example, the control rods and the fuel rods of the heterogeneous reactors may well be more conveniently fitted on mutually perpendicular axes. Also, the use of concrete for shielding is shown on all the reactors. Steel, lead or a composite structure could be more suitable. The probability is that lead will, in general, be found to be the most suitable shielding material for marine use.

### PRESSURIZED WATER REACTOR

The pressurized water reactor, as shown in Fig. 1, which is essentially as fitted in the USS *Nautilus,* has become the "pioneer" marine plant (7).

The fuel rods of the reactor could be of enriched uranium or plutonium, probably clad for strength with a metal, which has low neutron absorbing capacity, such as aluminum or zirconium. The control rods would be machined from a cadmium steel alloy or a boron steel alloy.

Highly purified water under pressure forms both reactor coolant and moderator to make the reactor operate at "thermal" energy level. For best heat transfer conditions in the reactor, the primary water velocity is increased by restricted passage

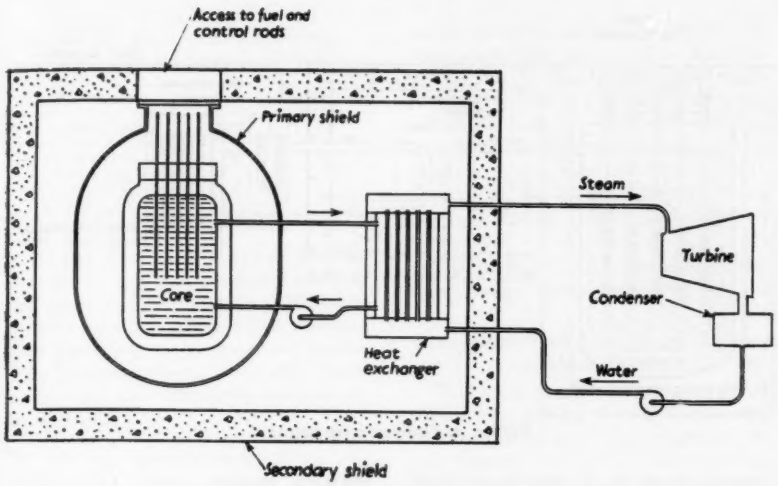



Figure 1. Pressurized water reactor.

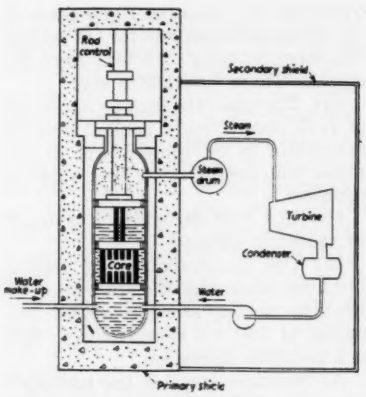



Figure 2. Boiling water reactor.

cross-sections. By maintaining a high rate of flow through the primary circuit, the temperature rise of the pressurized water is kept to a minimum.

Heat is transferred from the primary circuit to the secondary circuit in a tubular exchanger and the steam so formed is separated in the steam drum of the steam generator. Presumably this could be arranged for either natural convection or forced convection, depending on the steaming rate required.

One obvious disadvantage of this system is the impracticability of producing super-heated steam. As an example, assume the primary circuit water is pressurized to 1,000 p.s.i. abs., the maximum temperature in the primary circuit must be below the equivalent saturation temperature (544° F.). Allowing say, 10° F. loss during transmission to the heat exchanger and a mean temperature difference between the pressurized primary water and the evaporating secondary water in the heat exchanger of, say, 60° F., then saturated steam at 400 p.s.i. pressure will be produced.

The United States A.E.C. reactor of this type will generate approximately 300,000 kW. of heat which will be transferred to the heat exchanger by circulating water at 2,000 p.s.i. and 525° F. Saturated steam at 600 p.s.i. pressure will be generated in the heat exchanger and passed to a steam turbine generator which will have an output of some 60,000 kW. It is expected that this installation will be in operation late in 1957.

An inherent advantage of this system is that the expansion of water with temperature rise allows an increased leakage of neutrons and, hence, a system which to some degree is self-stabilized.

No claims are made that this type of reactor will produce economical power, but it is the type on which most experience is available, and, therefore, it could be claimed to be the most reliable. An improvement in neutron economy could be made by using heavy water instead of light water, and the thermal efficiency might be raised slightly by increasing the circulating water pressure. Pressure tightness of the system becomes of increasingly greater importance with either of these changes.

The principal bogy remains in the form of the efficient utilization of saturated steam.

### BOILING WATER REACTOR

Fig. 2 shows the boiling water reactor in which steam is generated by direct contact during water circulation through the core. The arrangement is thus a simplification of the pressurized water reactor in that one of the loops is eliminated. This, however, has two additional disadvantages. First, during the boiling process of the water, which acts as moderator as well as working fluid, the variation in density allows a variation in leakage of neutrons, thus causing a fluctuation in power level of the reactor. Secondly, the steam passing off to the turbine will be radioactive, thus producing an additional shielding problem. It seems likely, therefore, that the boiling water reactor would be operated at a lower power level than the pressurized water reactor. However, it is reported that the U.S. General Electric Company has expressed a preference for this design as a long-term possibility, and, indeed, experiments conducted at the National Reactor Testing Station in Idaho and at the Oak Ridge National Laboratory have confirmed that these reactors can give stable operation.

### HOMOGENEOUS REACTOR

The homogeneous reactor shown in Fig. 3 was designed primarily to

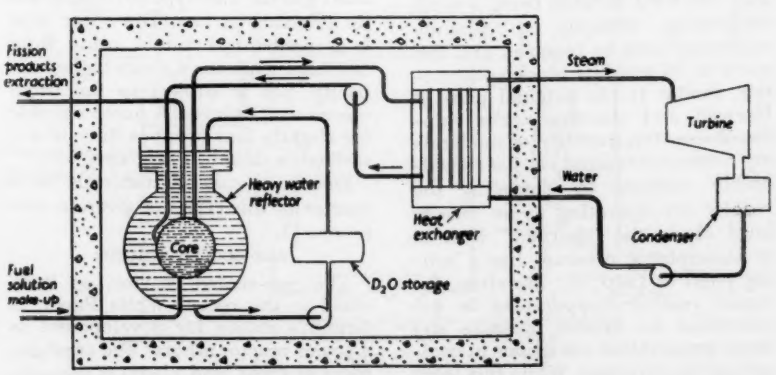



Figure 3. Homogeneous reactor.

overcome the essential limitations of the heterogeneous reactor, of which the two previous reactors are examples. These limitations are:

(a) The separate core components of fuel, control rods, coolant and/or moderator in the limited area of intense heat, create a real heat transfer problem.

(b) The core structure is subject to radiation damage.

(c) The accumulation of fission products caused by the absorption of neutrons necessitates the periodic removal of fuel for reprocessing. This is a complex operation.

As the name implies, the homogeneous reactor operates on an intimate mixture of fuel and coolant/moderator in the form of a solution of uranium salt in ordinary water. The primary circuit, through which this solution is circulated under high pressure, consists basically of the spherical container which forms the core and a restricted passage to the heat exchanger.

To summarize the characteristics of this homogeneous reactor, it could, therefore, be said that the nuclear stability or safety is purchased at the expense of providing a completely leakproof system for a highly radioactive and corrosive solution which is subject to a pressure of at least 1,000 p.s.i. The description and results of an experimental model of this type have now been published (8). It is interesting to note that although several leaks were experienced during the start-up phase, the plant finally operated for 12 months without any leakage being detected.

### SODIUM LOOP REACTOR

Fig. 4 shows the variant in heterogeneous reactor design using liquid sodium as a coolant. A version of this type of reactor is to be used on the second nuclear-powered submarine USS *Sea Wolf*. Sodium being a weak moderating material, a separate moderator will be required and this could be of graphite block construction similar to the original piles at Harwell and elsewhere. For shipboard use, the quantity of moderating medium required can be considerably reduced by designing the reactor for operating at an energy level above the "thermal." Sodium at atmospheric pressure has a boiling point of 1,600° F.; therefore, the upper reactor temperature is not controlled by system pressure and large temperature variations in coolant can be arranged. While this leads to design problems incurred in thermal stressing, it also overcomes one of the main application problems by allowing the production of moderately superheated steam (say, 600 p.s.i. and 800° F.). The higher level of reactor power output increases the degree of radioactivity in the sodium and this provides a more difficult shielding problem than is encountered in a thermal reactor. Also, the preparation of a sodium-cooled reactor for operation must include arrangements for external melting of the material prior to circulation in the system. In fact, an auxiliary oil-fired "boiler" will be required for this purpose.

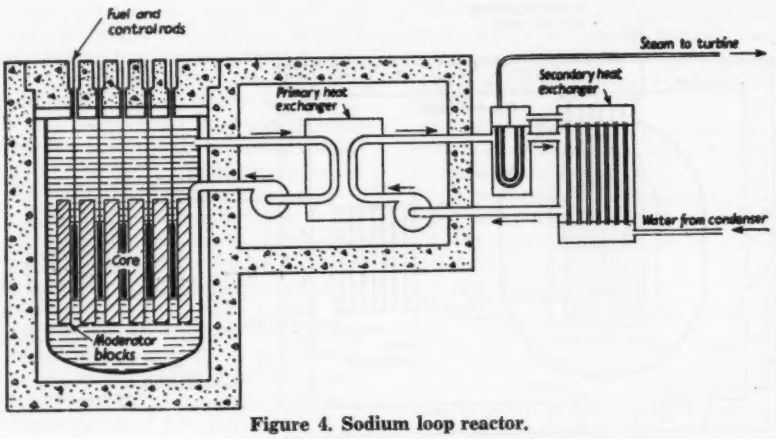



**Figure 4. Sodium loop reactor.**

Probably the major engineering problem to be faced with this type of reactor is the pumping of a liquid metal at a temperature of about 1,000° F. Any leakage would produce both a radioactive and a fire hazard. A typical specification for leakage tolerance is one cubic centimeter in 10 years and to meet this demanding service two types of pumps have been developed. One is an electromagnetic pump which eliminates the usual rotors and, consequently, the shaft glands. This type is reliable but its efficiency is low. The other type is a centrifugal pump using fluid bearings. This has a much higher capacity, but is subject to the usual mechanical failures. A pump suitable for slightly less arduous duty is described in detail in reference 10.

Details of suitable materials for a reactor of this type are given in reference 11.

### GAS-COOLED REACTOR

The gas-cooled reactor, as indicated in the recent White Paper, is Britain's choice for development as a power reactor ashore. The arrangement of these land plants is presumably as envisaged in the recent Institute Section paper (12). This provides for the reactor coolant gas to circulate a steam generator in much the same manner as existing types of waste-heat boilers, except, of course, that for the nuclear plant the gas would be in a closed circuit. The steam produced, again probably saturated, with its attendant complications would be utilized in a turbo-generator set.

The gas-cooled reactor shown in Fig. 5 is of the heterogeneous thermal type. The fuel could be slightly enriched uranium, the rods of which are clad with zirconium, aluminum or stainless steel to minimize neutron absorption. There is also the possibility of using fuel in powdered form sealed in a metal container, thereby reducing fuel reprocessing costs.

Preliminary designs and outlines of equipment have been prepared for a submarine installation (13) to compare the use of water, sodium, and helium as coolants in the nuclear power plant. The characteristics are summarized in Table II.

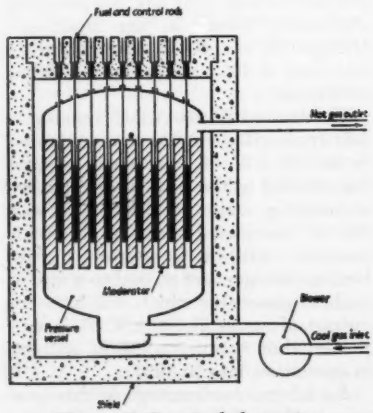



**Figure 5. Gas-cooled reactor.**

TABLE II—*Comparison of Water, Sodium and Helium as Coolants*

| Reactor coolant | Water | Sodium | Helium |
|---|---|---|---|
| Shaft power output.. | 0.90 | 1 | 1 |
| Overall plant weight. | 0.97 | 1 | 0.64 |
| Specific weight, lb. per s.h.p..... | 1.08 | 1 | 0.64 |
| Space occupied, cu. ft. per s.h.p.... | 1.10 | 1 | 0.66 |
| Shield Weight ..... | 0.77 | 1 | 0.51 |

Of the five reactor types already discussed, the marine application of the gas-cooled reactor, as outlined in a later section, offers what the author considers to be the most favorable balance between first and operating cost and simplicity and safety in operation.

### THE BREEDER REACTOR

Although not likely to be used as a shipboard power producer, some mention of this type of reactor is justified in that it seems likely that it will provide a definite link in the application of nuclear power to marine propulsion. This link could well be the production of fissile fuels, available to the marine industry and others, at a price lower than that at which uranium ore could be mined, processed and marketed.

Two reactions have proved of interest in the manufacture of fissile fuel. The first is that when the natural uranium U.238 is subjected to a bombardment of neutrons, as occurs in the core of a reactor, the nucleus picks up an additional neutron and thus becomes a new element or isotope, U.239. This has a nucleus which is not stable and, therefore, it decays to plutonium 239. The second is a similar reaction commencing with thorium 232 which captures an additional neutron to become Th.233 and then decays to U.233.

One of several groups of American power companies and machinery manufacturers, is now working on the design and development of a power plant using a breeder reactor. This represents what is probably one of the most advanced designs proposed and the reasons for its choice, despite the "pioneering" work required, merit quotation (14).

"Our reasons for selecting the breeder type of reactor were (a) our belief that a reactor which will produce both heat and fuel holds the greatest possibility of commercial success, and (b) our belief that large-scale use of atomic energy for power generation can be achieved only by utilizing a large part of the total heat potential of uranium, rather than the 3% to 7% which seems to be the limit of most thermal reactors which use U.235 or plutonium as fuel. A breeder reactor theoretically offers a possibility of using all of the heat potential of uranium, but from a practical standpoint it likely would succeed in utilizing only about 50%. At the same time it would produce more atomic fuel than it consumes."

The plant consists basically of the same design as shown in Fig. 4.

### NUCLEAR-POWERED CLOSED-CYCLE GAS TURBINE PLANT

The heat energy in the gas from the reactor can be directly converted to mechanical work in a closed-cycle gas turbine, and while the working fluid could be either air, nitrogen, carbon-dioxide or helium, the latter is preferred.

In this type of plant, only the reactor requires shielding, allowing a far more flexible machinery arrangement and a considerable saving in weight.

Helium has a better heat transfer characteristic than nitrogen, which is enhanced with increase in pressure. Thus, the heat transfer surface required will be reduced compared with an air or nitrogen system, but the high specific heat of helium makes the design of turbo machinery more difficult. The number of stages required for the same temperature rise is roughly proportional to the specific heat (1.25 B.T.U. per lb. for helium compared with 0.24 B.T.U. per lb. for air). However, the cycle analysis which follows will show that the compressor temperature ratio required for maximum cycle efficiency decreases with increasing recuperator effectiveness, and this fact is made use of in the design of closed-cycle helium plant by trading static heat transfer surface for stages of turbo machinery. The inert helium also removes the problem of chemical attack on the power plant components.

Several excellent articles and papers (15, 16, 17 and 18) discuss the merits of the closed-cycle air turbine and a large amount of the subject-matter applies to the helium turbine.

Fig. 6 is a diagrammatic representation of the suggested plant. Expansion is in two stages to isolate the power turbine from the compressor drive. Reversing can be accomplished by a reversible pitched propeller (19).

### CONTROL SYSTEM

The power output of this plant varies with the system pressure. This pressure level control is effected by addition or withdrawal of working fluid from the circuit, and emergency speed control of the power turbine is effected by by-passing.

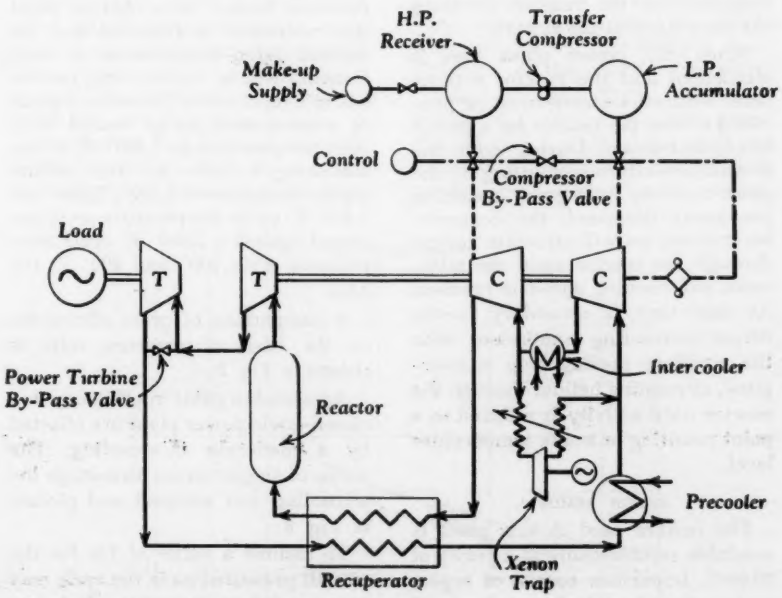



**Figure 6. Closed-cycle gas-turbine plant.**

Helium that is not being circulated in the plant is stored in accumulators for subsequent use, making this a no-loss system. The accumulator system consists of two (or two groups of) storage bottles, one being the receiver and the other the accumulator interconnected by a transfer pump. In this system, the total amount of helium in the power plant and tanks is constant at all times. Any leakage loss is made good by addition of helium to the receiver from time to time as required.

An overspeed governor is provided on both the high-pressure compressor-turbine set and the power turbine. The governor on the compressor-turbine set is a top-speed governor only, tripping a compressor by-pass valve when this set exceeds a predetermined speed limit. The governor on the power turbine is designed to come into play only in the event of an emergency the occurence of which makes it necessary to shut down the plant. In action, the power-turbine governor opens the power-turbine by-pass valve, immediately reducing the helium flow through the power turbine. Since this reduces the back pressure on the compressor drive turbine, it tends to overspeed, thus actuating the compressor by-pass valve. Further, the power turbine overspeed governor trips the system pressure regulator, resulting in the discharge of the contents of the system to the receiver. Simultaneously, the control rods are dropped into the reactor, reducing the heat input to the system.

When the power plant load is eliminated and the reactor activity level reduced, a means must be provided to cool the reactor for a period after shut-down. During both the normal procedure of shutting off the plant and the emergency condition previously discussed, the compressor/turbine set will circulate helium through the reactor until the minimum self-running speed is reached. At that time, a secondary, motor driven circulating compressor with the auxiliary cooling loop is energized, circulating helium through the reactor until activity is reduced to a point resulting in a safe temperature level.

### XENON REMOVAL

The helium used in this plant is available commercially at a purity of 99.99%. Impurities consist of argon, carbon dioxide and nitrogen, none of which is in sufficient quantity to be of concern. There is, however, the possibility of contamination of the system by gaseous fission products escaping from the reactor fuel elements. The principal volatile radioactive impurity of the fission process is xenon, and it is desirable that this be removed to prevent even a small build-up of radioactivity of the working fluid.

The xenon can be effectively removed to any degree desired by solidification in a cold trap.

A typical arrangement of this type of trap is shown in Fig. 7.

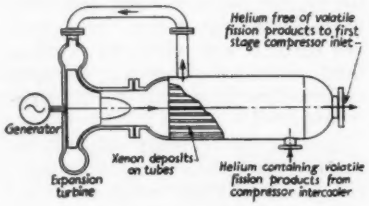

Helium free of volatile fission products to first stage compressor inlet
Generator
Xenon deposits on tubes
Expansion turbine
Helium containing volatile fission products from compressor intercooler

**Figure 7. Xenon trap.**

### CHOICE OF CYCLE DETAILS

In order for any closed-cycle nuclear power plant to be attractive economically, it must be a high-temperature machine, i.e., it must operate at cycle temperatures in excess of 1,200° F. All experience to date with closed-cycle power plants has been at a cycle temperature of 1,250° to 1,300° F., as dictated by the limiting tube wall temperature in a fired air heater. In a nuclear plant this restriction is removed and the turbine inlet temperature is only limited, within reason, by reactor outlet temperature. However, a plant of conservative design would limit such temperature to 1,500° F. In establishing a cycle for the helium plant, the values of 1,300°, 1,350° and 1,400° F. cycle temperature were assessed against a 1,300° F. cycle temperature with 100° and 200° F. reheat.

A comparison of cycle efficiencies on the basis of pressure ratio is shown in Fig. 8.

Appreciable gains in efficiency in a closed-cycle power plant are effected by a moderate intercooling. The value of single versus two-stage intercooling was assessed and plotted in Fig. 9.

To assume a value of 7% for the overall pressure loss in the cycle may be regarded as optimistic. It is believed that this value can be attained

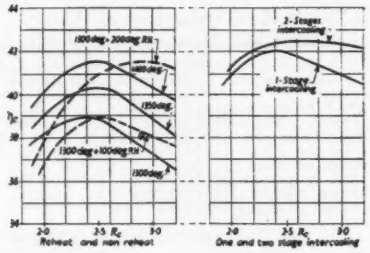



**Figure 8. (Left) Comparison of reheat and non-reheat cycles.**

**Figure 9. (Right) Comparison of single and two-stage intercooling.**

with careful design and without excessively large heat transfer surface. Referring to an air cycle plant, this is the equivalent of a total overall pressure loss of 11% assigning 5.5% total pressure loss to the reactor, which would be the equivalent pressure loss in a fired heater.

The assumption of a sea temperature of 75° F. will certainly be on the high side for the majority of steaming time and, when this is so, an improvement in cycle efficiency can be expected.

The effect produced on work rate and cycle efficiency with variation of overall pressure loss and sea-water temperature is plotted in Fig. 11.

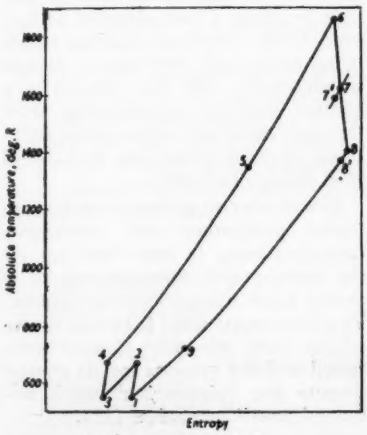



**Figure 10. Proposed cycle for helium plant.**

### ECONOMIC ASPECTS OF THE USE OF NUCLEAR FUEL

A power of 15,000 s.h.p. has been mentioned earlier as a minimum to fully exploit the advantages of the use of nuclear fuel. Crever and

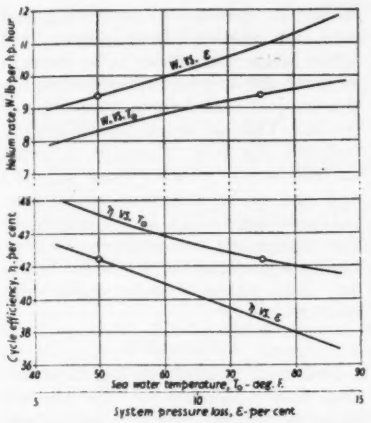

Helium rate, W-lb per h.p. hour
W. vs. ε
W. vs. $\eta_c$
Cycle efficiency, $\eta_c$ per cent
$\eta$ vs. $\eta_c$
$\eta$ vs. ε
Sea water temperature, $T_c$ - deg. F.
System pressure loss, ε - per cent

**Figure 11. Correction for off-design conditions.**

Trocki (13) make two significant comments on this consideration: (a) "As the amount of shielding is practically independent of power output, a nuclear power plant of low power will be penalized excessively with respect to its power output." (b) "Power plants for propulsion of larger ocean going vessels (of the order of 10,000 h.p. and above) are of sufficiently large power output to fall within the favorable range for a nuclear power plant of current design."

To illustrate the finance involved in powering a vessel today, estimates of propulsion machinery, derived from the costs for five ships are given in Fig. 12.

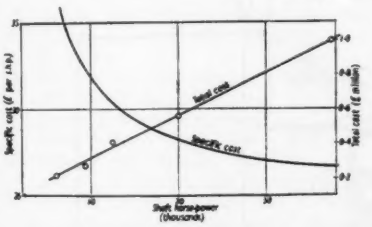



**Figure 12. Graph of cost estimates for steam turbine machinery.**

### HIGH-POWERED CARGO SHIP

An economic analysis has been made of the application of nuclear power to the "Mariner" class ships (20). These cargo vessels have a displacement of 21,000 tons and develop 17,500 s.h.p. to give a cruising speed of 20 knots. The maximum output is 19,250 s.h.p. and is, therefore, within the range considered feasible for nuclear powering. The design and operation of these ships is described in references 21 and 22 respectively.

The design study made in considering the use of nuclear power in a vessel of this class has not been published. It is presumed that a sodium loop reactor would be used to provide steam of sufficiently high superheat.

The conclusion reached from the economic analysis of a nuclear-powered "Mariner" was that it could not compete with the conventional power plants at present, but that the advance in reactor technology would improve the competitive position of this new power source.

### BULK CARGO CARRIERS

A survey of the most desirable conditions under which to operate a nuclear-powered vessel gives a good indication of the type of vessel most likely to benefit from its adoption. As a first requirement, a high-powered installation running on a long haul fully exploits the saving in oil fuel. Intermittent operation of a nuclear reactor is a wasteful procedure, as, at reduced loads, it is probable that arrangements must be made to "dump" the temporarily unused heat. Even on shutdowns, the reactor output can only be gradually reduced to prevent overheating. Thus, in both cases, a waste of valuable fissile fuel can occur. To minimize this loss, berthing and cargo handling time must be reduced. Another consideration is the special terminal facilities necesary to handle radioactive material. A shuttle service with fixed terminal ports would thus be desirable. Bulk cargoes such as ore, grain or oil are therefore indicated and the latter appears to be preferred, particularly as the offshore loading and discharge of oil cargoes is now an accomplished fact. This is an additional advantage both in reducing maneuvering time and in providing a safety measure by isolation. The choice of an oil tanker is not a paradox as it is inconceivable that the use of nuclear energy will reduce the demand for oil within a period of time equivalent to the combined lives of several ships.

An excellent review of modern tanker and ore carrier design practice is given in references 24 and 25. The specific vessel selected as suitable for analysis in this paper is described in references 26 and 27.

The deadweight capacity loaded is 30,000 tons and the model test speed-power-curve is reproduced in Fig. 13.

A comparison will be made between this ship and an equal-sized vessel powered by a helium cooled reactor and a closed-cycle gas turbine.

For the purpose of this analysis, a typical voyage from a North European port to either the Burma or Borneo oilfields will be considered, a steaming distance of, say, 10,000 nautical miles each way.

The fuel consumption for the whole voyage is estimated at 4,350 tons and the time 48 days. The "steaming cost" would be:—Fixed charges, 11%, £1,450 and oil at £7 per ton, £30,450, a total of £31,900.

In calculating the fissile fuel consumption of the nuclear plant, the heating value of 1 gram of U.235 is taken as $65.5 \times 10^6$ B.T.U. or equivalent to 25,750 horse-power hours.

The cycle developed in the foregoing section will be used and the cycle efficiency of 42.4% should not vary appreciably over the whole range of powers, this being a characteristic of the closed-cycle plant.

The estimated U.235 "burn-up" during the voyage is 1,954 grams (16,500 s.h.p.). This is the weight of fuel which is actually destroyed in producing the power for the voyage,

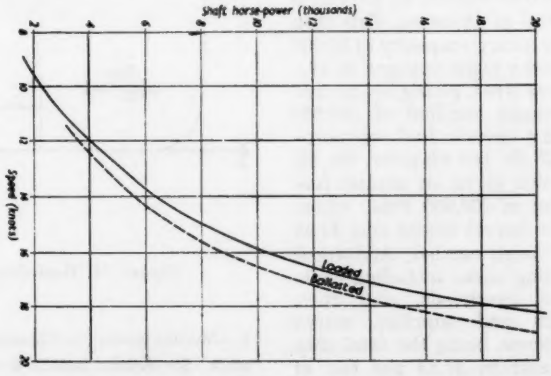



**Figure 13. Speed/power curves, loaded and ballast condition.**

but it only represents a fraction of the total fuel with which the reactor must be charged. A reasonable "burn up" percentage for the fuel for the heterogeneous gas-cooled reactor would be 25%. Following this burn-up the fuel elements would require chemical processing. The capital outlay for the plant, therefore, must include the cost of some 5,862 grams of U.235 carried as dormant fuel per voyage.

A detailed estimate of the first cost of the gas-cooled reactor is outside the scope of this paper, but, using the limited information available, a figure of £1 million, or 10 times the equivalent steam plant, agrees with majority opinion.

If the price of U.235 is £X per gram and using the same fixed charges on investment the "steaming cost" for the voyage then becomes £14,480 + 2,039X. To break even with the equivalent orthodox steam plant X must equal £8 10s. per gram.

At the international conference on the peaceful uses of atomic energy held in Geneva in August, 1955, the price of uranium was quoted at $25.00 per gram of U.235. It was not stated whether or not this figure included an allowance for fuel element fabrication. Even allowing for some error in this figure, then it would appear that a balance in "steaming costs" for the two plants could nearly be made.

The bunker fuel capacity of this 30,000-ton d.w. tanker is 4,500 tons and would be filled at the port of loading. Using a nuclear-powered plant would increase the machinery weight by some 500 tons, giving a net increase in cargo capacity of 4,000 tons.

### ALTERNATIVE PROPOSALS FOR TANKERS

To compare propulsion plants, Shoupp and Witzke (29) selected a tanker of 20,000 normal s.h.p. with a service speed of 18 knots. This ship would have a cargo capacity of 35,000 tons and make eight voyages of 17,000 miles per year, giving an annual total for cargo handled of 280,000 tons. Using a specific fuel consumption of 0.523 lb. per s.h.p.-hr. for all purposes, this gives an annual fuel consumption of 232,000 bbls., which at $2.00 per barrel would cost $1.65 per ton of cargo carried. Additional ship operating costs, including capital charges, overheads, port dues, maintenance and supplies, wages and subsistence, bring the total ship operating cost to $7.15 per ton of cargo.

Details of the type of nuclear reactor proposed for this ship were not available at the time of writing, but mention is made in the paper of the use of steam as the thermo-dynamic fluid. To compare the two types of power source in detail:

For equal costs:

(a) With zero nuclear fuel cost, the maximum permissible price for the reactor plant would be $4,800,000.

(b) Assuming zero investment in the plant, the nuclear fuel price cannot exceed $27.80 per gram.

This paper agrees that a saving will be made in the combined weight of plant and fuel and suggests that every 1,000 tons of additional cargo capacity can pay for an additional plant investment of $500,000.

Another proposal is made by the Engineering Research Institute of the University of Michigan. This is included in a recently completed feasibility and preliminary design study for a nuclear power plant suitable for a large ocean-going tanker (30).

The conclusion drawn from this study is that safe operation can be expected, but that there will be no saving in operational cost compared with an oil-fired installation. This latter factor was rather to be expected since the original specification for this project called for a tried type of reactor. This, of course, considerably reduced the field of choice. A pressurized water reactor was selected and one of its inherent advantages is illustrated in Fig. 14, which shows the convenient arrangement of providing a transparent shield by flooding the access hatch above the reactor.

### CONCLUSION

Following a study of the information now available on the various types of nuclear reactors and power plants, the author selected the helium-cooled reactor with a closed-cycle gas turbine power plant as the most attractive for commercial marine use. The economic comparison shows that this plant can compete with the oil-fired steam turbine plant for high-powered ships once the design values used in the paper have been verified in practice and the first cost of the plant proven to be of the order suggested.

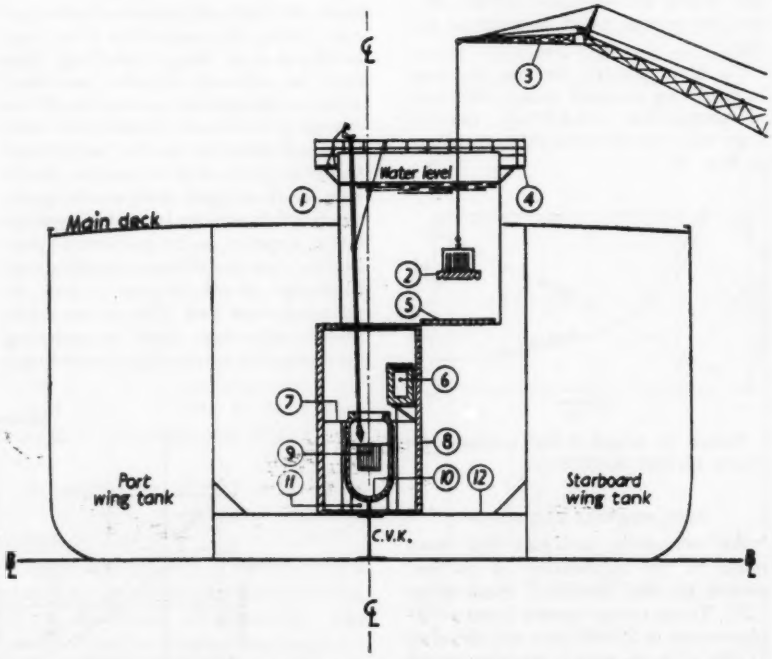



**Figure 14. Dockside handling arrangement for radioactive material.**

1.—Manipulators. 2.—Reactor cover and control rods. 3.—Dockside crane. 4.—Catwalk. 5.—Shield hatch. 6.—Cask. 7.—Watertight deck. 8.—Shield. 9.—Core. 10.—Pressure vessel. 11.—Reactor supports. 12.—Reactor foundation.

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JOURNAL OF THE FRANKLIN INSTITUTE

# RECENT DEVELOPMENTS IN THE TECHNOLOGY OF CERAMIC MATERIALS FOR NUCLEAR ENERGY SERVICE

ACKNOWLEDGEMENT

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CERAMICS—non-metallic materials capable of service at elevated temperatures—have several actual and potential applications in nuclear energy service. In particular, such materials are of interest in reactors intended for high temperature operations. They also have potential application because of their nuclear properties and corrosion resistance.

Physical research is carried out on ceramic materials under the sponsorship of the Atomic Energy Commission at a number of research institutions and it is the purpose of this paper to review some recent developments in this field.

## FUEL ELEMENTS

The bulk of the recent research and development efforts on ceramics and ceramic metal combinations (cermets) has been in the fuel element field because of the relative stability of ceramics at elevated temperatures and their resistance to corrosion in certain environments.

### *Uranium Oxide*

Many of the compounds of uranium are of interest for reactor use because of their higher service temperatures compared with the metal. In particular, the dioxide of uranium has received considerable attention because of its refractory nature and resistance to aqueous corrosion. Data on the uranium oxides are shown diagramatically in Fig. 1.

### *Differential Thermal Analysis*

DTA-weight gain measurements in the temperature range, 20° C. to 1000° C., have been used at the Oak Ridge National Laboratory as a method for rapidly indicating the oxygen contents and the reactivities of $UO_2$ powders prepared by various techniques. Figures 2 and 3 show some DTA weight-loss data for selected $UO_2$ powders. The DTA and weight-change curves indicate two oxidation steps $UO_2 \rightarrow U_3O_7 \rightarrow U_3O_8$. Both steps are exothermic. The initial oxides studied vary from $UO_{2.005}$ to $UO_{2.15}$, and in general the intermediate oxides vary from $UO_{2.34}$ to $UO_{2.38}$. These oxygen ratios were calculated on the basis that the uranium oxide was $U_3O_8$ at the maximum weight shown on the curves. In all cases a small weight loss, 0.0001 to 0.001 gram per gram of $UO_2$, was observed between 50° C. and 150° C. This loss in weight is probably due to absorbed water. The effects of particle size and degree of crystallinity of $UO_2$ powders on their reactivity and the final density of bulk $UO_2$ shapes made from them are being studied by this technique. It is observed that $UO_2$ prepared by methods yielding very small crystals react at lower temperatures whereas the oxides having large crystallites or small surface areas react more slowly at higher temperatures. By proper selection of starting materials, $UO_2$ in bulk form has been prepared by isostatic pressing and sintering at 1750° C., resulting in bodies having 96 per cent theoretical density.

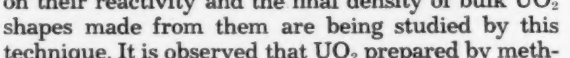


**Figure 1. Data on uranium oxide.**

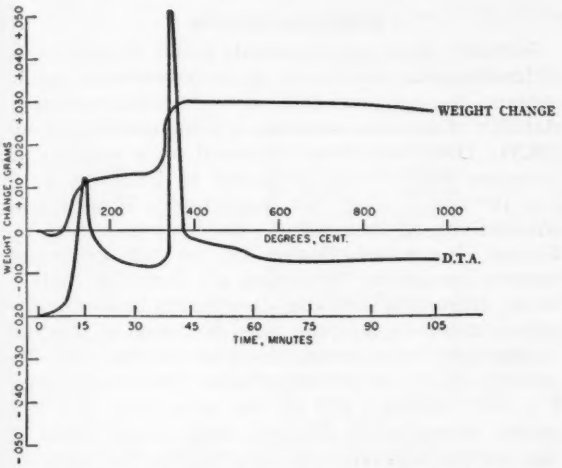


**Figure 2. Ammonium Diuranate PPT. $UO_2$ D.T.A. and weight change from $UO_2$ to $U_3O_8$.**

*Thorium Oxide*

Thorium oxide of potential interest as a breeder material is required in the form of shapes having maximum density. It has been found at ORNL (1)* that the addition of 0.5 wt. per cent CaO will produce bulk $ThO_2$ shapes having densities of 96 per cent of theoretical compared with 86 per cent for those made using $ThO_2$ without additions under the same firing conditions, that is, 1700° C. for 1 hr. A study of the effect of the addition of CaO indicates that the calcium is taken into solid solution in the $ThO_2$, producing anion vacancies. The diffusion of $Th^{++++}$, $O^{--}$ and $Ca^{++}$ is accelerated as a result of the vacancies and more rapid sintering occurs. The $Ca^{++}$ ion has about the same ionic radius as $Th^{++++}$, about 1 Å, so that solid solution is expected. A lowering of the index of refraction is noted as CaO is added to the $ThO_2$ up to 20 mol per cent. Chemical analyses show the CaO to be present after sintering, yet there is almost no measurable change in the unit cell dimensions of the $ThO_2$. The effect of CaO upon sintering is noted beginning at 1100° C. and is pronounced at 1600° C. There is no liquid phase in the $ThO_2$-CaO system below 2300° C. so that this is a solid state reaction. An investigation of the sintering rates indicates that surface diffusion is primarily responsible for the rapid densification of the $ThO_2$-CaO compacts. The mobility of $Ca^{++}$ on the surface of $ThO_2$ at high temperatures is high and almost immediately the pores in the pressed compacts are filled to the closed pore state. Volume diffusion of the $Ca^{++}$ and the $Th^{++++}$ and $O^{--}$ through the defect structure is much less rapid than migration over the surface but is sufficiently rapid to maintain increased sintering rates in the closed pore state.

*Cermets*

Ceramic metal combinations offer interesting possibilities for use in fuel element fabrication and for structural components of nuclear reactors. Two cermets of possible interest for reactor applications which have received recent attention are Cr-$Al_2O_3$ and SiC-Si. Work at the Ohio State Engineering Experiment Station (2) shows that consistently pore free bodies of moderate shrinkage can be fabricated from the compositions 72 per cent chromium-28 per cent alumina to give bodies having a density of 5.9. High temperature strength properties may be adequate for applications at 800° F. and above. Oxidation of this material is negligible at temperatures below 2000° F. The sustained load carrying ability shown by stress rupture behavior indicates that deterioration as a function of time is not extensive below 2000° F. Thermal shock resistance for this material is reported to be good. Siliconized silicon carbide may be prepared by the impregnation of a porous graphite body with molten silicon. The thermal nuetron absorption cross section of this material is about 0.1 barn. Studies at ORNL (3) resulted in the production of non-porous bodies of this material. The final density of this SiC-Si is 3.1; tensile strength at room temperature is about 10,000 psi., and thermal conductivity is better than that of stainless steel.

Silicon carbide bodies using SiN as the bonding agent and reported to have less than 10 per cent porosity have been developed. Self bonded silicon carbide density 96 per cent of theoretical has also been produced (4).

## MODERATORS

*High Density Graphite*

The efficiency of graphite as a moderator is roughly proportional to the density of the material. Commercial forms of graphite having densities ranging from 1.85–1.92 are produced by multiple impregnations of graphite with pitch. The average value for transverse breaking strength of 1.92 density material at room temperatures is 4500 psi.; modulus of elasticity $2.5 \times 10^6$ psi.; thermal expansion at 200° F. is reported as $1.1 \times 10^{-7}$ per deg. F.; thermal conductivity in Btu per hr. per sq. ft. per deg. F. per in. is 1200. The high density material has very good erosion resistance in high velocity gases compared with that of commercial graphite.

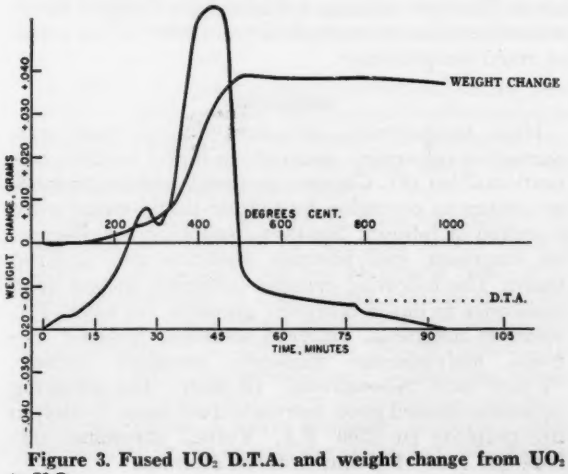


**Figure 3. Fused $UO_2$ D.T.A. and weight change from $UO_2$ to $U_3O_8$.**

*Numbers in parentheses refer to the references appended to this paper.

### CONTROL ROD MATERIALS

The rare earth oxides are materials of interest for reactor controls because of their relatively high absorption cross sections for thermal neutrons. In a study conducted by ORNL (5), $Sm_2O_3$ was found to form a ceramic of medium strength and density when fired in dry pressed form at 1300° C. Fired at 1500° C. the density is increased to 7.4 and the ceramic loses its stability to boiling water. $Gd_2O_3$ forms a ceramic of somewhat higher density (7.0) at 1300° C. than does $Sm_2O_3$. At 1500° C. its density is slightly higher (7.6) while its stability in boiling water is unchanged. Both $Sm_2O_3$ and $Gd_2O_3$ form compounds with $Al_2O_3$, BaO, $Fe_2O_3$, $SiO_2$ and SrO. The alumina and iron compounds have the perovskite structure previously observed in the case of yttria-alumina.

Hafnium oxide is also of potential interest as a reactor control material and investigation of this material at ORNL (6), indicated that halfnium oxide closely resembles $ZrO_2$. $HfO_2$ forms a continuous series of solid solutions with $ZrO_2$ and it forms a single compound with silica, $HfO_2 \cdot SiO_2$, similar to zircon. Monoclinic $HfO_2$ is stable to 1700° C.; the tetragonal form is found above this temperature. Boron carbide of compositions $B_4C$ and $B_6C$ have been produced in bulk form and also offer promise for control or shielding applications.

### COATINGS

Ceramic coatings developed for service at 1000° C. have been prepared by the National Bureau of Standards (7) from materials having low absorption cross sections for thermal neutrons. They were specifically designed for application to typical high temperature alloy parts for use in nuclear reactors. In these coatings, high-barium frits containing small amounts of phosphates, beryllia, lime, zinc oxide and titania are milled with additions of ceria or mixtures of chromic oxide and ceria. The computed neutron absorption cross sections are in the range of 0.15 to 0.50 barn. In extended heating tests some corrosion was noted beneath the coatings but the amount and depth were markedly reduced over uncoated specimens. The best coatings withstood the thermal shock encountered when quenched from 2000° F. in water at room temperature.

### CORROSION

High temperature corrosion studies were conducted on refractory materials in liquid sodium, bismuth and tin (8). Ceramic materials exhibiting good resistance to corrosion by sodium liquid-vapor were reported as follows: Synthetic sapphire, single-crystal magnesia, molybdenum disilicide and sintered thoria. The following ceramic materials show a good resistance to liquid bismuth: graphite (to 1400° F.), sintered magnesia, sintered alumina, sintered zirconia, molybdenum disilicide, tantalum carbide, "Vycor" and "Kennametal" (K138A). The following ceramics showed good corrosion resistance to molten tin: graphite (to 1500° F.), "Vycor," chromium carbide (to 1500° F.) and sintered alumina.

### RADIATION EFFECTS

Stability of ceramic materials under irradiation is of fundamental importance in nuclear reactor applications. A comprehensive survey of the radiation stability of ceramic materials is being carried out by ORNL. Data have been collected on a number of ceramics which were subjected to irradiations of $1 \times 10^{20}$ and $2 \times 10^{20}$ *nvt*, respectively. The thermal conductivity at about 40° C. has been measured by Sisman, Bopp and Towns (9) on the irradiated ceramic specimens. These data are shown in Table I. X-ray diffraction indicated disordering in some crystalline materials. In some cases decreases in thermal conductivity were found where no changes were detected in X-ray difraction patterns. Zircon irradiated $2 \times 10^{20}$ neutrons per sq. cm. gave very low and poorly reproducible thermal conductivity before a thin surface was removed by scraping. For many of the materials there was not much additional change in thermal conductivity with the longer exposure ($2 \times 10^{20}$ neutrons per sq. cm.). It was suggested that possibly the change is approaching saturation. X-ray diffraction patterns of the irradiated specimens were made by Klein (10) and qualitatively compared to the patterns of the corresponding samples before irradiation and the results are shown in Table II. It should be noted that the method of X-ray analyses for polycrystalline samples with a high activity count is not so sensitive in detecting weak X-ray reflections as the method used for small single crystals of the same materials. Consequently, where the method used in this study would indicate the absence of detectable diffraction lines in certain cases, the single crystal analysis might still indicate a few reflections remaining in the film pattern after a comparatively long exposure time.

TABLE I.—*Thermal Conductivities[a] of Irradiated Ceramics[b]*

| | Thermal Conductivity ($10^{-4}$ cal · $sec^{-1}$ · $cm^{-1}$ · $°C^{-1}$) | | |
|---|---|---|---|
| | | Postirradiation[c] | |
| Material | Preirradiation | $nvt=1\times10^{20}$ | $nvt=2\times10^{20}$ |
| Silica glass | 35 | | 35 |
| Single-crystal $Al_2O_3$ | >300 | | >300 |
| Hot-pressed $Al_2O_3$ | >300 | | >300 |
| BeO | >300 | | >300 |
| $TiO_2$ | 200 | 120 | 110 |
| Spinel | >170 | 100 | 100 |
| Forsterite No. 243 | 180 | 43 | 43 |
| Cordierite No. 202 | 77 | 23 | 21 |
| $HfO_2$ | 80 | 30 | 30 |
| Steatite No. 228 | 60 | 28 | 28 |
| Mica | 21 | 14 | 13 |
| $ZrO_2$ No. 550 | 33 | | 25 |
| Zircon No. 475 | 120 | | 21 |
| Zircon No. 71 | 49 | | 28 |
| Plate glass | 30 | 30 | 30 |
| Pyrex glass | 36 | 30 | 20 |
| Lead glass | 16 | 10 | 10 |

[a] In the temperature range from 35 to 45° C.

[b] C. D. Bopp, O. Sisman and R. L. Towns, "Solid State Semiann. Prog. Rep. Aug. 30, 1954," ORNL-1672, p. 90.

[c] Exposures are given in epithermal neutrons.

TABLE II.—*X-Ray Examination of Ceramic Samples*

| Sample | Results When Irradiated with $1 \times 10^{20}$ neutrons/cm² | Activity (at 1 cm) | Results When Irradiated with $2 \times 10^{20}$ neutrons/cm² | Activity (at 1 cm) |
|---|---|---|---|---|
| Single-crystal $Al_2O_3$ | No change in pattern | 1.5 mr/hr | No change in pattern | 1.5 mr/hr |
| Hot-pressed $Al_2O_3$ | No change in pattern | 6 mr/hr | No change in pattern | 10 mr/hr |
| Spinel | No change in pattern | 1.5 mr/hr | No change in pattern | 5 mr/hr |
| Forsterite | No change in pattern | 15 mr/hr | No change in pattern | 60 mr/hr |
| Porcelain | No change in pattern | 40 mr/hr | No change in pattern | 40 mr/hr |
| Steatite | No change in pattern | 80 mr/hr | No change in pattern | 80 mr/hr |
| $TiO_2$ | No change in pattern | 170 mr/hr | No change in pattern | 230 mr/hr |
| Silica glass | Halo broadening | 2 mr/hr | Halo broadening | 2 mr/hr |
| Plate glass | Halo broadening | 10 mr/hr | Halo broadening | 15 mr/hr |
| Pyrex glass | Halo broadening | 10 mr/hr | Diminution in halo intensity; broadening | 30 mr/hr |
| Lead glass* | Lead plus other devitrification products | 500 mr/hr | Lead plus other devitrification products | 900 mr/hr |
| Mica | Line broadening; 1.3% expansion in $c_0$ | 120 mr/hr | Line broadening: 1.7% expansion in $c_0$ | 170 mr/hr |
| Enamel ground coat | Loss in crystallinity | 6.7 r/hr | Loss in crystallinity | 11 r/hr<br>7 r/hr (gamma) |
| $ZrO_2$ | No change in pattern | 6 r/hr | 0.28% expansion in $a_0$ | 10.4 r/hr<br>600 mr/hr (gamma) |
| Hf-free $ZrO_2$ | Diminution in monoclinic phase | 800 mr/hr | Monoclinic phase disappears; cubic phase remains | 1.2 r/hr |
| Zircon | 1.9% expansion; large loss in crystallinity | 2.2 r/hr | No lines detectable; large loss in crystallinity | 6.8 r/hr |
| SiC | Line broadening; 0.3% expansion | 10 mr/hr | Expansion and loss in crystallinity | 10 mr/hr |
| BeO | Very slight expansion in $c_0$ | 9 mr/hr | Approximately 0.3% expansion in $c_0$; none in $a_0$ | 25 mr/hr |
| Lava | Loss in crystallinity | 170 mr/hr | No lines detectable | 220 mr/hr |
| Cordierite | No change in pattern | 100 mr/hr | Line broadening | 150 mr/hr |
| MgO | No change in pattern | 15 mr/hr | $MgO + MgO{\cdot}4CO_2{\cdot}5H_2O + MgCO_3{\cdot}3H_2O$ | 15 mr/hr |
| $BaTiO_3$ | 2.03% expansion in $a_0$ | 80 mr/hr | 2.87% expansion in $a_0$; reflections broadened | 170 mr/hr |

*Confirmed by petrographic analysis.

Under irradiation, quartz alters gradually to an amorphous form. Some of the property changes reported by Wittels, Oak Ridge National Laboratory (11), and Primak, *et al.*, of Argonne National Laboratory (12), are decreases in density, refractive indices, and birefringence, disappearance of the alpha to beta transition and changes in the absorption spectrum. The properties of vitreous silica also alter under irradiation. The density and refractive indices increase slightly. On heating the irradiated quartz and other forms of silica, the properties are reported to alter in a complex manner.

### OTHER APPLICATIONS OF CERAMICS IN NUCLEAR ENERGY

Present methods of disposing of radioactive wastes are safe for limited quantities but in many cases, extremely expensive. Work is being done on the application of cheaper methods of handling such wastes (13). One possibility which has received serious study at the Brookhaven National Laboratory is a method of adsorbing the wastes on clay pellets. The pellets are then glazed in a furnace so that the products cannot seep out and it is proposed that these pellets can be safely buried. Various clays and other minerals have been found under certain conditions of pH and temperature to have a great affinity for radioactive wastes. Table III shows the result obtained in jar tests on the removal of radioactive materials by various clays and vermiculite as reported by Brockett and Placak (14). They point out that base-exchange ratings do not indicate the efficiency of clays or soils for removing radioactive materials from solution and further conclude that although certain removals are obtained with one chemical form of radioisotope it does not necessarily follow that the same results will be obtained with other chemical forms of the isotope.

At ORNL studies are being carried out on the possibility of incorporating radioactive liquid wastes in a ceramic body in pits and fixing the dangerous isotope by sintering the mass in place using the heat available from radioactive decay.

Contributions in the field of glass technology include the development of windows which do not darken under radioactive bombardment. Such windows are necessary in order to see into the ray filled interiors of hot labs. These windows are so heavy that one measuring $6 \times 8$ ft. weighs about 12 tons (15). Another interesting development in the glass industry has been the manufacture of radiation dosimeters which are pieces of silver activated phosphate glass that indicate by darkening the amount of radiation to

TABLE III.—*Removal of Radioactive Materials by Various Clays.*
(Brockett and Placak)
(Jar Stirring Method with 1 Gram of Clay)

| Sample Number | Type of Clay Locality | Per Cent Removals after 2-hr Contact | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | $Ce^{144}$ $3.9\times10^{-2}$ uc/ml | $P^{32}$ $3.5\times10^{-2}$ uc/ml | $Ru^{106}$ $4.8\times10^{-2}$ uc/ml | $Sr^{89}$ $1.1\times10^{-2}$ uc/ml | $Sr^{90}$ $4.1\times10^{-2}$ uc/ml | $Zr^{95}$ $0.78\times10^{-2}$ uc/ml | MFP* $4.1\times10^{-2}$ uc/ml |
| 1. | Kaolinite ..... Mesa, Alta, N. Mex. | 92.50 | 51.58 | 69.39 | 30.40 | 46.25 | 98.08 | 70.87 |
| 2. | Halloysite ..... Eureka, Utah | 91.82 | 72.90 | 77.95 | 26.15 | 61.63 | 98.32 | 89.77 |
| 3. | Montmorillonite ..... Little Rock, Ark. | 69.21 | 88.27 | 64.40 | 63.03 | 74.50 | 97.18 | 94.70 |
| 4. | Montmorillonite ..... Cameron, Ariz. | 89.00 | 31.89 | 52.89 | 57.44 | 71.35 | 91.05 | 92.44 |
| 5. | Nontronite ..... Manito, Wash. | 85.16 | 44.56 | 60.77 | 29.26 | 71.49 | 92.25 | 94.75 |
| 6. | Metabentonite ..... Tazewell, Va. | 76.05 | 68.28 | 53.61 | 16.10 | 53.46 | 83.59 | 86.20 |
| 7. | Metabentonite ..... High Bridge, Ky. | 88.20 | 80.05 | 68.08 | 41.75 | 59.87 | 97.13 | 86.16 |
| 8. | Conasauga Shale ..... Oak Ridge, Tenn. | 90.91 | 72.67 | 71.69 | 14.15 | 55.69 | 96.63 | 86.88 |
| 9. | Vermiculite (nonexpanded) ..... Sylva, N. C. | 95.94 | 60.15 | 68.69 | 26.77 | 65.53 | 93.87 | — |

*Mixed fission products ~16% $Ce^{144}$, ~20% trivalent rare earths, ~2% $Ru^{106}$, ~20% $Sr^{90}$, ~21% Cs, ~21% unknown.

which they have been exposed. They are finding use in studies made in the food sterilization field.

Glass and glass-metal pipes and valves may be of interest in future handling of radioactive process solutions. Tests at ORNL indicate no gross damage to commercial glass-piping and glass-metal specimens in such solutions having an activity level of $10^8$ counts per min.

This short summary has covered some of the highlights in the developments in ceramics for nuclear energy service and it is hoped that it will serve to give an indication of the applications of ceramics in nuclear energy service.

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COMMANDER ROBERT J. KNOX, U. S. Navy

# *TWENTIETH CENTURY "CLERMONT'S" FIRST CRUISE*

*graduated from the U. S. Naval Academy December 19, 1941. He served as Engineer Officer of the USS MacLeish (DD220) and the USS Hunt (DD674); in the latter he also served as Executive Officer. In June 1948 he received his Master's degree in Mechanical Engineering from the U. S. Naval Postgraduate School, and began working with the USS Timmerman experimental machinery at the U. S. Naval Boiler and Turbine Laboratory, then the Supervisor of Shipbuilding, Bath, Maine and finally as Engineer Officer of the USS Timmerman. In July 1954, after three months as a ship superintendent, he became the Destroyer Type desk in the Boston Naval Shipyard, and in May 1955 he became the Shop Superintendent. Commander Knox has contributed previous articles to the* JOURNAL.

## INTRODUCTION

IN FEBRUARY 1954 an article entitled "Twentieth Century *Clermont*" was published in the JOURNAL of the American Society of Naval Engineers. The attached article is written so as to present some of the earlier sea experiences of that same ship, USS *Timmerman* (EAG152).

One must understand certain basic research and development principles to understand *Timmerman*. She is an experimental engineering destroyer which was designed to be a floating laboratory. All designs of her machinery were intentionally made so close in every respect that the designers could anticipate a failure in one or more parts. These failures in turn would point out where they had cut a little too close in their attempt to go "off into the blue." The evaluation of the engineering equipments, therefore, is a cut and try method similar to any research problem. One must have patience.

I write of *Timmerman* as of July 1953. In those days *Timmerman* was known as EDD-828; she is now EAG-152. At that time she had all her guns and was regarded as a regular fleet 2200-ton destroyer, and to all outside observers she appeared to be almost identical to any other fleet destroyer. She has since had her guns removed. Duty on board at that time, and in many ways even today, was a tedious, demanding job and, at times, became very discouraging. There were other times, however, when it was the biggest thrill in the world.

Although it has been two years since I left the ship, I look back with pride to the engineering crew. As you read the article I want you to particularly note the short time intervals, during the various casualties that have been listed, to see the superb performance that was exhibited by the individual man on the job at the time of the casualty. There were times, you will note, in which casualties were taking place in each of the four engineering spaces simultaneously. It would have been impossible to assume that any Chief Engineer or his Division Officers, or any particular chief could be ready and available to be immediately upon the scene of a casualty at any one time. It was, therefore, necessary to see that each man knew his job absolutely.

Since this first cruise, she has completed a run at 30,000 SHP per shaft for four hours. This equals the ability of any of our present fleet destroyers. On 18 December 1955 *Timmerman* returned to Boston after a six weeks cruise to Key West, Florida. Many of the problems described in this article have been eliminated. The Key West cruise was a tremendous success by comparison. As a further proof of *Timmerman's* increasing reliability, she spent 36 hours in a hurricane and her only real problem was oil leakage from the #1 cruising turbine forward bearing.

## TWENTIETH CENTURY *Clermont's* FIRST CRUISE

At 0119 on 13 July 1953, an entry was made by a sailor in the rough log of the USS *Timmerman* (EDD828) as follows, "Emergency Generator went

Dead." At the time, that emergency generator was our last source of power. We were moored to a buoy in the harbor of Newport, R.I. A northeaster was just beginning to show its teeth; and the *Timmerman* went dead—no lights, no ventilation, no heat, not even coffee, nothing but battle lanterns. Battery powered lights were hoisted to substitute for navigational lights; P-500s (gasoline driven fire pumps) were started to provide fire and flushing system pressure, and by morning a line was formed outside the door of Sickbay as men, with coffee pots in hand, awaited their turn to use the bunsen burner to brew a pot of coffee.

I will never forget that day and I'm sure all hands who were on board will certainly not forget it either. To many it was like the Jones boy who had gone bad. To others, who were familiar with the engineering plant, it was a normal expected step which was necessary. Few babies learn to walk without a fall, few champions reach the top without bruises—*Timmerman* was no exception to these rules.

Slightly more than a month before this casualty, we had steamed out of Boston on both engines with four generators in operation (two ship service and two emergency). Less than two weeks after this casualty, we steamed back into Boston on both engines with four generators in operation; but, there is more to this than a mere statement of fact.

Since commissioning, 26 September 1952, and prior to 9 June 1953, the vessel had been to sea only on 14 March, 3 April, and 22 April 1953; a total of 23 hours with no greater speed attained than 31 knots (268 rpm) on two boilers. On 9 June we took our first step to "make like a ship." The net result of that first step was to cover a period of six weeks, 2488 miles, 19 operating days at sea at an average speed of 15 knots, and the greatest period of underway training in engineering casualty control the Navy has probably ever experienced.

This article will deal with the high points of that experience. My remarks will be limited to facts based upon entries made in the ship's Engineering Log. It will not be necessary to resort to exaggerations.

*9 June 1953*

0831 the USS *Timmerman* got underway from Boston Naval Shipyard for Provincetown, Mass. The pump which provides cooling water to the #2 turbo generator was out of commission. There is a standby cooling system for this generator in the form of an eductor actuated by water from the firemain. As long as we had at least two fire and flushing pumps on the firemain (or two emergency fire pumps), we had nothing to worry about. On this day we had only two pumps available (#3 and #4 fire and flushing pumps, both #1 and #2 emergency fire pumps being out of commission).

0842 placed #2 emergency fire pump into commission.

1615 #3 fire and flushing pump was placed back into operation and we felt like a high school boy with hair on his chest. We steamed 11 hours during the day with a top speed of 16.9 knots. Our average speed, however, was only 10 knots for the day because the after bearing on the #1 high pressure turbine was running hot.

1949 we anchored at Provincetown just as the Worcester tornado passed through our anchorage.

*10 June*

0300 inspected the #1 high pressure turbine after bearing. The manufacturer's representative was with us. The bearing was in good shape so we enlarged the orifice in the lube oil line and reassembled the unit. The shaft driven lube oil pump bevel gears had shown a tendency in the past to try to chew their way through each other. We inspected them, the vendor relieved the tooth clearance with a file, and we reassembled the casing.

1349 underway. The #1 emergency fire pump was placed in commission.

1354 five minutes after the ship was underway and had worked up to 15 knots, the #1 low pressure turbine began to vibrate. Upon request from the engineroom, the bridge slowed to 5 knots.

1413 by increasing speed with 5 rpm increments, we reached 10 knots and the vibration had been eliminated.

1435 #3 fire and flushing pump went out of commission. #1 emergency fire pump proceeded to spend the remainder of the day in and out of commission by "blowing" its controller.

1618 the vacuum on #1 main condenser dropped to 15 inches of mercury. We did not determine the cause for this drop until we opened the condenser the next day and found fresh fish covering two-thirds of the inlet tube nest.

1725–1740 #2 distilling plant was down for repairs to the salt water heater drain pump. We were soon to learn that the pumps on this distiller would be a continuous problem.

2217 the oil seal on the planetary reduction gear began to leak oil. By reducing the pressure to 12 psi on the system the leak was stopped. The vessel steamed all night, with speeds between 10–15 knots.

*11 June*

During the day #3 fire and flushing pump was placed back into commission.

1514 the bridge commenced practice in maneuvering with the main engines.

1624 #1 low pressure turbine began to vibrate.

1655 with a repeat of the above "tenderizing" treatment, the vibration had disappeared.

1900 we anchored at Provincetown.

During this cruise, when at anchor, the vessel kept both turbo generators lighted off and operated entirely split plant. We still did not trust the turbo generators to the extent of securing one of these units even while at anchor.

A further complication to this arrangement, was the fact that it was necessary to jack-over the #2 main engine when operating the #2 turbo generator. The vessel has never received the auxiliary feed and booster pump for the after plant. This requires, therefore, the operation of the main feed and booster pump when in port. It's steam consumption is so great that the condenser on the #2 turbo generator (which is the auxiliary condenser) cannot handle the auxiliary exhaust steam. Blowing the excess to atmosphere would not only be a great loss of feed water but it also increases the back pressure on the main feed and

booster pumps. This increased back pressure has been suspected as contributing to past main feed and booster pump failures. The net result, therefore, is that we used the main condenser to handle the excess auxiliary exhaust, and still do.

*12 June*

0555 underway.

1207 #2 low pressure air compressor motor controller went up in flames and the boys had a little fire drill in the after engineroom.

1322 #2 low pressure air compressor was back in comsion.

1350 worked up to 25 knots.

1409 slowed down because the forward bearing on #1 cruising turbine was running hot.

1500 anchored for the weekend at Provincetown. The #2 jacking gear was given a rest and the excess auxiliary exhaust was sent forward to #1 main condenser.

*13 June*

0941 #2 turbo generator was secured until 1145 for some minor repairs.

*14 June*

Sunday was a good day to us. Liberty was granted in Provincetown and our sailors were able to go ashore in a "foreign" port like real sea faring men—imagine, no pier alongside! Quite a few wives and girl friends drove down from Boston to meet the liberty boats at the landing. You would have thought we had been to Korea and back. Most of those wives had been with us in Philadelphia and Bath, Maine, as well as in Boston. They had become a part of the "828" too and the first cruise was a thrill to us all.

*15 June*

0505 underway.

0514–0609 we toyed with the #1 low pressure turbine to eliminate vibration. By this time it was a foregone conclusion that we would get vibration if we tried to go ahead at any speed in excess of 5 knots after either an extended astern bell or after we had been lying-to and spinning main engines for more than 10–15 minutes. Continued operation further verified that conclusion.

0833 the vessel anchored in Boston outer harbor to take on ammunition.

1230–1900 #1 engine was put out of commission to check the orifice plate in the lube oil line to the #1 cruising turbine bearing (the one which had overheated on the 12th). A dispatch was sent ashore to the vendor requesting instructions. No obstruction was found in the orifice plate, no instructions were received from the vendor, so we reinstalled the same orifice plate. As frequently occurs with the equipment on the *Timmerman*, the bearing has run cool ever since.

2115 #2 automatic combustion control air compressor went out of commission.

2147 #2 main lube oil service pump went out, and we had to stop jacking the port engine and send the auxiliary exhaust steam forward to the #1 main condenser. At first it was believed that the bearings had failed on the main lube oil service pump. As we were wringing our hands over the possibility of not being able to get underway the next day on schedule, we learned that it was merely the controller which had failed. Controller and bearing failures were a regular occurence to us by this time, and meant no more to us than the fact that we just didn't know when or where our next engineering casualty drill would start.

2330 the lube oil pump was back in commission.

*16 June*

0801 underway.

0825 we had to stop #1 main engine as the result of low boiler pressure on #1A boiler. A pin had dropped out of 1A2 forced draft blower automatic combustion control linkage. In short order, the vessel was underway on both engines again.

1700–1915 #1 distiller circulating pump went out. This distiller, like #2, was to be out of commission periodically. That night we anchored off Scituate and granted liberty for the crew.

*17 June*

A fairly casual day. Underway at 0833.

1115 the laundry broke down. This machine was in and out of commission continuously during its first year with the more extended periods being spent out of commission. At one time, serious thought was given to exchanging it for a standard unit. The problem of obtaining a proper power supply for the unit was one of the laundry's saving graces. Following a period of repair and redesign by the manufacturer, the machine operated for an extended period before collapsing again. During the day, we worked up to 25 knots and held various drills.

1602 Moored alongside the pier in Boston Naval Shipyard.

The representatives of the automatic combustion control companies were on board during the cruise, and they had managed to work a good many kinks out of their respective systems. On our return to Boston, the vessel maneuvered quite radically for a little over a half hour. Both firerooms were on full automatic combustion control, except for steam to the blowers, and the bridge reported there was only one puff of black smoke. The men in the forward fireroom who were on watch at the time thought it was wonderful. With the control system installed in that fireroom it was only necessary to stand in front of the boiler and watch the show.

The after fireroom controls are used continuously in port and underway. The forward fireroom system is a little more complicated. This forward system cuts burners in and out automatically, both air register and oil pressure. It needs more operation and adjustment before the crew will be able to rely upon it. (There have been sufficient primary engineering problems to date, so that we have not been able to concentrate on the use of automatic combustion control operation in the forward plant.)

The purpose for the return of *Timmerman* to Boston on 17 June was to make repairs as the result of structural test firing damage which had been caused by the 5" battery. The firing cam permitted mount #2 to fire a little too close to the starboard side of the bridge and the blast damaged the O1 level. The aluminum superstructure was not prepared for such treatment; rivets popped, welds cracked or sheared, shields buckled, and life jacket lockers bulged. Engineering wise, we felt the ship was in as good or better condition than when the vessel had left the yard a week before.

**U.S.S. TIMMERMAN entering the Harbor of Havana, Cuba**

There had been so many remarks about "Building 828" in the shipyard and about our "concrete foundation" that I had vowed when we sailed that I'd stay out until I had to come in on a tow line. The Repair Officer in the shipyard was so glad to see us go that first day that he came down to see, with his own eyes, that *Timmerman* sailed. Our return was like old home week. The Shipyard Commander, the Planning Officer and the Production Officer all came down to see the Commanding Officer on our return. It was one of our greater days.

After five days in the yard we set sail for Newport, R.I. It was planned to give the vessel a period of "independent ship exercises," a trip to Washington, D.C., and then six weeks of shakedown training.

*23 June*

0820 underway with one fire and flushing pump (of four), both emergency fire pumps, and one auxiliary machinery salt water circulating pump (of two) in commission. The auxiliary circulator for #2 turbo generator was still out and so was #1 low pressure air compressor. I keep referring to our firemain and low pressure air systems because they were so vital to our operation. Without firemain pressure, it meant #2 turbo generator and the main feed and booster pumps aft, as well as the boiler circulating pumps aft, had no cooling water and would consequently become inoperative. Without low pressure air it would require a double watch to man all stations in the after fireroom, and even then, there would be no control on the desuperheater station. To pack more power into the same space means increased speed of operation of machinery and increased steaming rates for the boilers. To do this, automatic controls become a necessity. They are far superior to manual control, and there is little doubt in my mind but what they are the coming thing.

0830 #1 main condenser lost vacuum and the forward plant underwent a little "round robin." The man on the deaerating feed tank in the fireroom took on a slug of water and the exhaust pressure dropped in response to the need for more heat in the deaerating feed tank. The augmenting valve from the 300 psi line opened to bring the exhaust pressure up. The reducing station, which supplies the 300 psi line, is apparently too small and the result was a loss of pressure on the 300 psi line. The air ejectors which operate by steam from the 300 psi line consequently could not do their job and we lost vacuum. In two minutes everything was squared away.

0845 the chief boilerman in the after fireroom was burned by steam when the regulator on the steam supply to the main feed and booster pump became erratic. The pump overspeeded, lifted the main feed relief valve and the feed flashed to steam as it hit the bilges under the chief. The burn was the extent of a bad sunburn, so he was fortunate.

It should be of interest, that the *Timmerman* had only two men in the engineering crew injured during the vessel's operations the first year. In the other case, the man was burned with hot oil when the oil sump on the same feed and booster pump exploded. The pressure was released through an opening for an oil level dip stick and the man was directly in line with this opening at the time of the explosion. In his case he was also able to continue with his routine duties.

0932 the last fire and flushing pump was lost, but it turned

out to be another controller failure and the pump was back on the line by 0949.

1035 the regulator on the other main feed and booster pump in the after fireroom jammed (the shift had been made when the chief boilerman was burned). Operation was then shifted back to the first pump.

1124 the boiler in the after fireroom lost steam pressure when the fires went out.

1125 stopped the port shaft. Low pressure air to the automatic combustion control equipment had been lost and the failure had closed the fuel oil regulating valve.

1126–1132 the bridge held a steering casualty drill.

1135 we had started #2 automatic combustion control air compressor and lighted off the boiler again.

1138 the vessel's speed of 20 knots had been resumed.

1612 the vessel slowed to 15 knots when the low pressure pinion bearing on the after main engine became hot.

1640 the bearing temperature was normal.

1727 fog was encountered.

1912 & 1929 steering casualties were experienced.

2035 the fog lifted.

2200 a report came to me that 2A boiler circulating pump would have to be placed out of commission because of a cracked packing gland on the pump end.

2221 2B main feed and booster pump relief valve on the feed line lifted again and dumped the water from the deaerating feed tank in to the bilges. The water level in the boiler began to fall with the loss of feed pressure.

2222 stopped the port shaft.

2223 shifted the after electrical load to the forward generator.

2224 secured 2B boiler. Since the morning casualty when the main feed and booster pump regulator jammed, repairs had been made to that regulator to permit partial operation of the regulator in an emergency. That time had come, the pump was placed into operation.

2227 the boiler was lighted off again. #2 main engine lube oil service pump failed. The forward engineroom immediately stopped the starboard shaft. The main condensate pump which had been in operation on the after plant also failed.

2229 the port shaft had been locked by backing on the starboard screw and by using the after boiler steam pressure to hold it until it was locked.

2232 regained lube oil pressure (controller had tripped out when the main condensate controller "blew").

2308 unlocked the port shaft.

2320 checked the main lube oil strainers aft and found no metal.

2321 port engine answered a 5 knot bell.

2330 the main condensate pump was back in commission (during the casualty we had shifted to the standby pump).

2346 the main feed and booster pump was not getting enough steam through the emergency rig on the jammed regulator. Boiler pressure was lowered to a point which would permit feed to enter the boiler and a restriction of 5 knots maximum speed was placed on the port engine. (By-passes for the steam regulators are not installed.)

*24 June*

The *Timmerman* slid into Newport at a speed of about 5–7 knots as if she had not a care in the world and moored at 1017. For the first time anchored or moored in a harbor, we placed the entire ship's load on #1 turbo generator, and secured the after plant to lick our wounds on the main feed and booster pumps.

*25 June*

A test run was made on 2B main feed and booster pump after the oil sump had been checked for metal and the thrust readings had been taken. We were in luck. The pump had apparently survived the casualty without wiping the, then well known delicate, thrust bearing.

*26 June*

An emergency job by a tender on a new gland for the 2A boiler circulating pump placed it back in commission.

*27 June*

Both low pressure air compressors in the engine room were out of commission. Each fireroom has its own air compressor for combustion control. The low pressure air compressors in the engine rooms are primarily for ship service and secondarily as a standby source for the automatic combustion control systems. With both low pressure air compressors out of commission, the only standby supply for ship service use is the high pressure air compressor through a reducing station.

*29 June*

The vessel shifted its mooring to another buoy. On securing the main engines #2 turbo generator was used to carry the ship's load. In short order we were again involved in an unscheduled engineering casualty control drill.

1126 a loose connection on #2 turbo generator control system began to smoke. The emergency diesel generator was started and the load shifted to it.

1148 the gas turbine emergency generator was started to carry the forward half of the ship's load.

1156 fires were relighted under boiler 1B.

1200 the entire load was taken by the diesel generator when it became necessary to secure the gas turbine.

1222 #1 turbo generator took the electrical load of the ship.

1225 the boiler circulating pump on 2B boiler was placed out of commission and consequently 2B boiler was out of commission. The packing had blown out of the pump end.

1230 as we were eating lunch the electric load was lost and the diesel started again.

1244 #2 turbo generator was placed in commission after locating and securing the loose connection.

1251 #1 turbo generator had the ship's load again.

1505 shifted the electric load to #2 turbo generator.

1514 lost the electric load and shifted back to #1 turbo generator.

1640 back on #2 turbo generator.

I distinctly remember going down to the forward engineroom when the load was lost the second time. It was hot and steaming and I was tired. Officers, chiefs and petty officers were charging around busily handling the casualty. I sat down on the rag can and if I could have found a buyer I'd have sold *Timmerman* for one good Indian blanket at that moment. I didn't care if it sank right at the buoy. Thanks to the others in the engineering gang who were of a little

lighter mood at the moment, they soon had everything well under control.

*1 July*

The day was routine except that #1 turbo generator was out of commission most of the day for repairs.

1355 #1 automatic combustion control air compressor was placed back into commission.

*2 July*

0917–1140 an admiral and his staff, assisted by personnel from another destroyer, held an administrative inspection of the ship. The official report came out as a "very high excellent."

1600 the vessel was underway for none other than Bath, Maine, and a 4th of July weekend at our "First Home."

When we had been delivered, almost nine months previous, a standing invitation had been made for us to come back to Bath on the 4th of July. Each time our fitting out completion date in the Boston Naval Shipyard was pushed back we'd comment, "If this doesn't stop pretty soon we'll never make Bath by the 4th." At last that time had come.

Only one thing marred our getting underway and that was the test of the whistle. It was tested four times before a satisfactory test was obtained.

1740 we were making 25 knots.

1758 we shifted to our shaft driven lube oil pumps.

1823 it was necessary to slow because of an oil leak on the #1 low pressure turbine after bearing.

1827 a speed of 25 knots was rung up for the port unit and a speed of 21 knots was held on the starboard, #1, unit.

2042 the vessel commenced fog signals. The high pressure air compressor (both low pressure air compressors were out) was unable to produce the capacity of low pressure air through the reducing valve to keep the whistle lowing. The hand powered fog horn had been broken out and placed on the forecastle. Each time the man on the forecastle would blow it, one of the lookouts on the bridge would report he heard a fog signal close by, or just ahead, all of which would temporarily throw the bridge personnel into a panic. This situation was further aided by the fact that the surface search radar had just gone out of commission, we were off Nantucket Light Ship, and there were eight to ten contacts on the radar screen when the casualty had occurred. With conditions as such on the bridge we had our "trouble trio" on watch. At least they were soon to be identified as such. They were: (1) the Operations Officer on the bridge, (2) the Main Propulsion Officer in the forward engineroom, (3) the Auxiliary Gang Chief in the after engineroom. (Good men, but they had a nose for trouble.)

2127 fires were lost under the after boiler when low pressure air pressure was lost.

2128 rang up stop on the port engine.

2129 relighted fires under the after boiler.

2130 secured the boiler. Steam leak in the after engineroom.

2131 abandoned the after engineroom except for one man who stayed behind to secure the #2 turbo generator. The diesel emergency generator started on automatic.

2133 General Quarters (battle stations).

2134 #1 turbo generator took the full ship's electric load.

2138 auxiliary exhaust valve in the cross connect line in the forward engineroom jammed partially open.

2139 steam leak at the seal ring in the #2A guarding valve stopped.

2158 lighted fires under the after boiler again.

2211 split the auxiliary exhaust by closing the cross connect valve in the after fireroom.

2215 opened the guarding valve; slight leak. Surface search radar back in commission.

2217 #2 turbo generator back on the line with the after half of the ship's load.

2219 all ahead 10 knots.

2222 secured from General Quarters. Ready to answer all bells.

2309 the fog lifted enough to stop fog signals.

2340 the whistle was considered back in commission for navigational signals.

It just happened that I was writing my weekly report, of sorts, to our Bureau of Ships liaison officer prior to the above casualty. It strikes me as rather amusing to note the comments I made just before and just after the casualty.

> "Just slowed to 5 knots—don't worry, only to show movies on the fantail. Ship will now probably proceed to fall apart. It was so peaceful just steaming along at 23 knots!!
> What did I tell you—'They want me on the bridge.'
> Bob
>
> P.S.
> So I went to the bridge. The whistle wouldn't blow loud enough and we are in a fog. Result of investigation—when bleeding off the H.P. Air Compressor you do not have the volume for whistle. As I watched the whistle the after stack belched black smoke. I picked up the hand phone (for smoke watch) to hear what was on the engineers telephone line and heard, 'Mr. Cleveland we are abondging ehi aflea spaocl.' Came an answer, 'What?' From the other end came no answer. Main steam valve had sprung a leak and drove them all out of the after engineroom. Now 1½ hours later we are underway again. What did I tell you—steady progress. GOOD NIGHT."

*3 July*

0846 the after boiler lost fires and the port shaft came to an emergency stop. Two minutes later all problems had been resolved.

0910 the #2 automatic combustion control air compressor went out of operation.

1233 the vessel passed Fort Popham Light abeam to port.

1330 moored alongside the DL3 at Bath Iron Works.

1400 #2 turbo generator took the load while we did a fast repair job on a steam leak on the #1 auxiliary air ejectors.

1535 #1 turbo generator was back in commission and took the ship's electrical load. (It had been planned far in advance to steam the #1 turbo generator at Bath so as to eliminate the possibility of having to blow auxiliary exhaust steam to the atmosphere. A man must have his pride and a sailor is no exception.)

1600 #1 refrigeration compressor motor failed.

*4 July*

An uneventful day, as far as casualties to engineering equipment.

*5 July*

0936 #1 automatic combustion control air compressor went out of commission. With all low pressure air compressors out of commission it was now necessary to resort to our last source of air pressure, the high pressure air compressor.

It had been noticed by this time, and particularly on our trip to Bath, that the starboard stern tube was losing oil at an excessive rate, when underway. We struck down the remaining lube oil we had on hand for the stern tube bearing and calculated that there would be enough to get us back to Newport, where we had an order awaiting our return.

2305 the #2 emergency fire pump went up in flames.

While at Bath the weather was unusually hot. The ship was sitting in the sun and there was no breeze, which made conditions even worse. Fortunately the air conditioning units operated. The effectiveness of our air conditioning is reduced greatly by two factors. First, the amount of traffic in and out of air conditioned compartments at a time when the air conditioning is really needed results in almost eliminating the effect of air conditioning. During the holiday weekend, traffic was at a minimum and air conditioning was very good until the sun began to bear down upon us. That brings up the second factor. The overheads of all spaces which have a weather deck above, are insulated only on the flat areas between the longitudinals and the beams. The faces of the longitudinals and beams are not insulated. The result is a network of radiant heaters from 1000 to 1600 on each sunny day.

*6 July*

0829 the vessel departed Bath, Maine, for Newport, R.I. Everyone had had a wonderful time. Many friends had been formed by the ship's personnel during the pre-commissioning period at Bath. As one proud resident of Bath later wrote to me, "I saw the *Timmerman* sail down the Kennebec that morning—and without a tug." On both the sea trial and the delivery run down the Kennebec, a tug had followed the *Timmerman* as a precaution. This peculiar procedure was therefore particularly noted by the people of Bath who have a very keen interest in the Bath built ships.

0845 the bridge force was given a little thrill when there was a momentary steering casualty. Some people on the scene say it was just a sluggish response to the helm at a tense moment, but with that narrow rocky river I am sure the thrill must have been there.

1010 the vessel cleared the river.

1018–1145 the #1 turbo generator was secured for a quick repair job.

As the vessel headed for Newport, our "slip was beginning to show." All low pressure air compressors were out of commission. The same was true of three of our four fire and flushing pumps, one of our four boilers, one of our two distilling plans, one of our two refrigeration compressors and one of our two emergency fire pumps.

*7 July*

0055 the vessel anchored off Block Island.

0555 the other refrigeration compressor went out of commission.

0940 underway.

1018 the starboard engine was slowed to 15 knots because of an oil leak on the planetary gear.

1045 #3 fire and flushing pump was placed back in commission.

1107 #2 refrigeration compressor was back in commission.

1130 the planetary gear oil leak did not stop so the motor driven lube oil pump was secured and operation was continued with just the shaft driven pump.

1143 the forward fireroom could not blow tubes on 1B boiler because of a leaky drain valve.

1450 after mooring in Newport harbor, #2 turbo generator took the ship's load. About this time a fresh water barge came alongside to deliver water. We had been unable to operate our distilling plants in the river at Bath and the distilling plant at the Iron Works had been secured for the holiday weekend.

1502 #2 distilling plant was back in commission.

*8 July*

0755 underway after pouring 75 gallons of lube oil into the starboard stern tube oil tank.

0906 vacuum was lost on #1 engine.

0910 all was normal again.

1113 the vessel commenced passing mail and towing drills with another ship.

1237 shifted the electric load to #1 turbo generator to be able to secure #1 emergency fire pump for repacking.

1305 work completed on #1 emergency fire pump and secured #2 fire and flushing pump to replace a plug in the discharge line gage fitting.

1315 the plug was replaced and the load split again.

1328 lost fires on the after boiler when the #2 turbo generator tripped off the line; shifted load to the #1 turbo generator.

1335 the engine order telegraph failed.

1342 electric load split again.

1430 engine order telegraph back in commission.

1729 while lying-to and spinning main engines, #2 throttle linkage became disconnected when a pin fell out. Fortunately the valve was in the closed position at the time and the pin had fallen to a flat area of lagging where it was readily located. In three minutes we were on our way.

1746–1812 was spent "tenderizing" #1 low pressure turbine again.

1750–1930 1B boiler was out of commission for repairs to the drain valve.

2020 anchored. #1 emergency fire pump was placed out of commission for a bearing replacement.

2110 lowered the oil pressure on the planetary gear to 8 psi, while jacking, to stop the oil leak.

*9 July*

The day was utilized working with a submarine on sonar runs after getting underway at 0208. No casualties were experienced with speeds up to 25 knots being made on the port engine. Speeds on the starboard engine were limited to 23 knots to avoid oil leaks from the #1 low pressure turbine after bearing.

*10 July*

0705 underway with observers for a surface firing practice. In four minutes, the vessel went from the first bell to full speed (20 knots). The starboard turbine never even attempted a vibration. Shortly thereafter, we went to our maximum speed combination.

0829 slowed to 20 knots to investigate a knock in the planetary gear. The knock disappeared as soon as both engines ran at the same speed.
1124 #1 turbo generator tripped out on overspeed and fires were lost on the forward boiler. One minute later everything was stable once again.
1310 General Quarters for firing.
1315 #2 fire and flushing pump tripped out. Firemain pressure dropped.
1316 secured air conditioning unit #1 to save salt water cooling pressure.
1317 shifted load to #1 turbo generator and let #2 turbo generator idle with 80 psi firemain pressure for cooling. (Speed of 20 knots was maintained for the firing run in spite of casualties.)
1335 #2 fire and flushing pump back in commission.
1337 load split again. .
1626 after lying-to, vibration was noticed on the cruising turbine of the #2 main engine when getting underway. It was stopped by slowing to 5 knots.

*11 July*

The #2 auxiliary condenser circulating pump was returned to the vessel.
The pump was installed by 2002 and was out of commission by 2010.

2105 #2 turbo generator cut out on overspeed. Repeated tries to put it back on the line failed.
2340 #2 turbo generator was logged out of commission.

*12 July*

0656 Sunday, started off with a bang when #1 turbo generator overspeeded after losing voltage. The emergency diesel generator started on automatic.
0701 started rolling #1 turbo generator again.
0720 put it out of commission after it had been determined that the exciter was short circuited.
0919 broke out both P-500s and secured all power in the ship, except to the after plant, for another try at lighting off the #2 turbo generator.
1030 a young chaplain had boarded us that morning to carry out his assigned duties. Divine services were conducted amid a variety of weird noises. The sermon was the shortest I have ever heard, but the prayer was in earnest.
1223 secured #2 turbo generator because of malfunction of the hydraulic valve in the governor. Secured the after plant.
1245 secured the P-500 which was in operation and shifted to #2 fire and flushing pump. Cut in power to the rest of the ship from the emergency diesel. With both plants secured no feed water could be made from the distilling plants. When lighting off a cold plant, without the other plant in operation, auxiliary exhaust had to go to the atmosphere with a resultant loss of feed water during the entire evolution. The consequence was a rapid reduction of fresh water and feed water in the vessel's tanks. Showers throughout the ship were secured.
1644 a water barge had been kind enough to come alongside with its duty section to give us fresh water. All hands made a dash for the showers to assist us in getting the maximum amount of water from the barge.
2248 energized a P-500, secured #2 fire and flushing pump and again proceeded to light off the after plant.

*13 July*

0114 it began to happen! The upper bearing on the emergency diesel generator failed. The after plant was immediately secured.
0119 the gas turbine emergency generator was started but it tripped out on overspeed. It could not be restarted because the high pressure air system had been depleted by the initial start.
0215 by this time a check of the upper bearing on the emergency diesel had been made and the bearing lubricated. Since there was no air to start the emergency diesel generator, one of the 50 pound $CO_2$ bottles was connected to the air starting line. It started the generator, but also blew the muffler off. The explosion sent the telephone talker leaping right over the top of one of the officers as the telephone talker decided to depart. The officer came stumbling out of the compartment after a swallow of $CO_2$. The bearing froze to the shaft again about that same time and the show was over.

Cold iron watches were set and the duty fire party was mustered in the after mess hall and told to sleep there for the rest of the night. Battery lanterns were hoisted to the yardarm and at various other spots topside to double as standing lights for navigational purposes. The P-500s were tested and put on standby and we went to bed. What else could one do?

The morning weather was so bad that we could not get our liberty party on board until noon, and then, only by the use of tugs. The P-500s had become wet and would not start when needed at reveille. A little handy billy pump was used for the flushing system in the interim until we were able to place the larger pumps into operation.

1210 a tug delivered 50 gallons of gasoline from the Coddington Cove Fire Department, as we were running low on gasoline for the P-500s.
1530 underway by tug to go alongside the tender. Within two hours we were receiving all facilities from the tender, including power to run the shore power motor generator set.
1828 lighted off the forward boiler.
2000 #1 turbo generator started to roll.
2250 secured #1 turbo generator.
2330 lighted fires under the after bolier.

*14 July*

0042 #2 turbo generator was rolling.
0205 secured same.
1025 shifted ship's load to the gas turbine emergency generator for an hours test run and then shifted back to the motor generator set. (The air banks had been charged by a high pressure air line from the tender.)
1350 tested 2A boiler circulating pump motor. It would not come up to speed. With 2B boiler out of commission and a steam starting line to only the boiler circulating pump on that boiler, it looked like our entire after plant could not be lighted off. By filling boiler 2A with 300 psi steam through a circuitous route from the forward boiler, we were able to boost the motor on the boiler circulating pump just enough to light off boiler 2A at 2258.
2330 started rolling #2 turbo generator and secured the forward boiler.

*15 July*

0115 secured #2 turbo generator. Between runs on each turbo generator, repairs, adjustments, and investi-

gations were made to try to solve our problems. By this time we were receiving assistance from the vendors by telephone and directly as their representatives would come on board with more replacement parts.

1315 secured again.
1400 lighted off boiler 1A.
1535 started rolling #1 turbo generator. With the exciter gone on the #1 turbo generator, the electrical gang used the degaussing circuit to provide the excitation for the generator. Since the power on the ship, which included the excitation for the generator, was coming from the shore power set, it was going to be a bit tricky to switch to #1 turbo generator for power without losing excitation. It worked, however, but only for a short time. The voltage control was on manual control. The operator was not quick enough to keep up with the needs of the voltage control and the generator overspeeded. The overspeed trip did not operate (it was later found to be broken) and for a few seconds it looked like the generator would walk across the engineroom before it could be secured.

*16 July*

2210–2308 rolled #2 turbo generator again.

*17 July*

1045 rolled #1 turbo generator. Power was extremely important to us at this time because the New England area was experiencing a heat wave. The ship needed air conditioning badly. Many vent sets, which recirculated air in the compartments, were out. The air conditioning units were operating on a hit and miss basis and in general it can be said that the vessel experienced very little time in which there was a comfortable spot on the ship. Awnings were rigged on the main deck and many men slept topside to avoid the hot compartments at night.
1320 #1 turbo generator was secured again.
1730 rolled #1 turbo generator again.
1901 #1 turbo generator took the ship's load.
1947 lost the load and shifted back to the motor generator set.
1958 back on the #1 turbo generator.
2012 lost the load again and back on the motor generator set. Secured for the night.

*18 July*

1453 #1 turbo generator took the load. By using the motor generator exciter to excite the turbo generator, #1 turbo generator was placed in commission. Since the tender had been supplying us with all the feed water we had been using, we lighted off the #1 distilling plant.

*19 July*

0957 lost excitation and consequently power when the tender lost power.
1115 power was restored to the tender and to us.
1158 on #1 turbo generator again.
1412 shifted to the motor generator set to repair oil leak on #1 turbo generator.
1640 back on #1 turbo generator.

*20 July*

1420 #1 turbo generator overspeeded and tripped out. The load was shifted to the motor generator set.
2323 the tender lost the electric load, again, and also firemain pressure for a short while. Although we were beginning to operate our own generators, we felt for reliability, it was more practical to take firemain pressure from the tender until our electrical equipment had become more stable.

*21 July*

We continued to use the shore power motor generator set for power while making repairs to the throttle valves of the #2 turbo generator.

*22 July*

1116 the #2 turbo generator took the ship's load and was placed into commission, after a check run was made to determine the success of the repairs. The emergency diesel was also placed back into commission. To help our ego a little, we ran a test on the emergency gas turbine generator and it too was satisfactory.

*23 July*

This date had been set as our departure date to return to the Boston Naval Shipyard for repairs. Another destroyer was to steam with us—"just in case." Difficulty was encountered with #1 turbo generator as we were preparing to get underway. By using the degaussing system to excite the generator in combination with the control panel for the motor generator exciter, we were able to eliminate the need for manual control of the voltage.

1000 the vessel got underway for Boston with #2 turbo generator on the line and the #1 turbo generator still objecting to taking its share of the electrical load.
1013 #1 low pressure turbine started to vibrate.
1015 the #1 main condenser circulating pump stopped with a horrible bang and was placed out of commission. (Other than the forward fireroom main feed and booster pumps, which were actually DL2 pumps, the main circulator pumps were the only pumps on the ship which had not required repair prior to this time.) The bridge was informed that we could not go faster than 10 knots because of the vibration in the #1 engine; we could not go less than 10 knots because of the #1 main circulating pump being out of commission. (I don't recall ever having been in a spot like that before.)
1057 the vibration had disappeared.
1458 #1 turbo generator took part of the electric load.
1718 while blowing tubes on 1B boiler, the universal on the reach rod to the soot blower valve carried away. The vessel steamed with speeds up to 20 knots, with an average of 17 knots, throughout the night.

*24 July*

We proceeded to the outer anchorage of Boston to rendezvous with the ammunition barge to unload ammunition.

0600 #2 turbo generator took the entire ship's load and #1 turbo generator was secured for emergency repairs.
0622 began to secure #1 main engine by letting the starboard screw drag as we entered the channel on the port engine. In an emergency we could have answered a short bell, particularly an ahead bell, but with the #1 main circulator out of operation it was considered best to drag the shaft and let the engine cool down.
0647 anchored and locked the #1 shaft.
1055 placed #1 main engine circulating pump back into commission after removing a lobster float from the pump impeller. By removing a "dutchman" in the

line, we were able to let a man crawl into the pump and locate the float.

1252 #1 turbo generator took part of the ship's load again, and we were soon underway; steaming with two main generators, two emergency generators on standby, two boilers, three fire and flushing pumps, the high pressure air compressor for all air requirements, complete split plant and ready to answer all bells from the bridge.

1335 moored to the pier at Boston Naval Shipyard. To our complete amazement, the starboard stern tube did not leak oil on the return trip to Boston. There has been no explanation for its peculiar conduct other than the possibility of dirt having passed through the seal and temporarily scratched an oil groove in it. Since this peculiar occurance removed the necessity for dry docking the vessel in hot weather, every one was happy over the coincidence.

During the above experiences, there was almost as much activity on the bridge at times as there was in the engineering spaces. The Gunnery Officer had introduced a poem to the engineers while at Bath which really began to become popular as the days went by. Although the poem itself covered several situations, there was one particular section which appealed so much to me and seemed to become more and more appropriate to our experiences that I not only read and reread the poem but soon began to quote the following portion. It is taken from a poem entitled, "DE KULLISION HON DE HOSHUN" and the only acknowledgement indicated is, "Courtesy USS *Augusta*."

"Adt dees mument rong de bozzer,
'De Chiff requests a liddle pow-wow,
Weet de Keptin esks hen hudience.'
Spuk de Chiff dees wuds what follow:
'Keptin, I am werry sorry—
But I hup you won get worrit,
Mebbe we can feez de trubble,
mebbe eet ess nut so turrible.'
Wit sigh de sturbud hingine,
Stodded hup hen huffle racket,
Halso stopped de odder hingine
Gafe a gasp de furward hairpomp,
Wid a beng de hefter boiler,
Wid a hees de furward fireroom,
Stopped eet opp de floshink seestem.
Lost de sockshun hull de hoil pumps,
Lost de prassure hull de boiners,
Gafe a laff, 'Ha, Ha,' de helmsman."

On 21 March 1956 the Navy announced the award, to the Shipbuilding Division of the Bethlehem Steel Company, Quincy, Massachusetts, of a contract to conduct design studies for a nuclear propulsion plant for a surface warship. The contract does not include design of the nuclear reactor or construction of the ship.

The designs will be for a nuclear propulsion plant suitable for combatant surface types in the 8,000 to 12,000 ton range.

# *HIGHLIGHTS OF REACTOR TECHNOLOGY 1942-1955*

**ACKNOWLEDGEMENT**

*Dr. M. C. Leverett, Engineering Manager of the Aircraft Nuclear Propulsion Department of General Electric Company, is the author of this article. It was published in the November, 1955, edition of "General Electric Review."*

At the University of Chicago's Argonne Laboratory, when in 1942 for the first time man initiated a nuclear chain reaction, those present sensed the importance of the occasion. For a few moments on that historic December afternoon, thoughtful speculation and discussion centered on the uses of atomic energy other than in the destructive bomb. A glance at the 13 intervening years will show what has happened in the exciting, demanding, and complicated field of reactor technology.

Growth in this field can possibly be measured by the different types of reactors built and the number of new groups who have built them since 1942.

The first reactor of the chronology is, of course, the graphite-moderated reactor called CP-1—the key actor in the drama just described. During the following year, the CP-2 quickly succeeded the original reactor. It had no cooling system and never ran at more than a few kilowatts for any sustained period, although occasionally it operated at higher power for short periods. The reactor's fuel was uranium and its oxides; its moderator, graphite; and its shield, concrete. Although little more than a large critical experiment, the usefulness of this reactor lasted for a long time.

The graphite reactor at the Oak Ridge National Laboratory went into operation that same year. This reactor was a large cube of graphite pierced with many holes in which aluminum cans containing uranium cylinders, or slugs, were placed. Fans pumped air through the space surrounding the cylinders. A series of minor changes in design and auxiliary equipment gradually increased the initial power of approximately 800 kw to several times this figure.

Really the first power reactor, it produced energy at so low a temperature as to be almost useless. However, in postwar years a miniature steam boiler was constructed and put into the reactor, which heated it by nuclear processes. The steam produced drove a tiny generator, and the resultant power lit an electric lamp—quite possibly the first example of useful electricity from a nuclear chain reaction.

In 1944 the first reactors of really high power—the graphite-moderated water-cooled reactors—were put into action at Hanford. For fuel elements they also used uranium cylinders canned in aluminum to protect them against the action of the cooling water.

During the same year the first heavy-water-moderated reactor was put into operation, also using aluminum-clad uranium slugs as the fuel elements. These were bathed in heavy water that served both as coolant and moderator.

Also in 1944, Los Alamos introduced the first homogeneous reactor—the type known as the water boiler—that used a solution of enriched uranyl nitrate in water.

No new reactor types were placed in operation during the next two years. But in 1947 the Canadians began to operate the so-called NRX reactor. Although moderated with heavy water, it was cooled with light water. And uranium slugs again clad with aluminum served as the fuel elements.

Another year passed before the first fast neutron reactor came to life at Los Alamos. Its fuel was plutonium, its coolant mercury.

In 1950 a lineal descendant of the Oak Ridge graphite reactor was put into operation at the Brookhaven National Laboratory, Long Island. This air-cooled

reactor used uranium slugs canned in aluminum. Certain engineering techniques greatly increased its power over that of the Oak Ridge reactor.

Placed into operation in 1951 was the first of the alkali-metal-cooled reactors: the sodium-potassium-cooled U-235 fueled fast-neutron Experimental Breeder Reactor (EBR), built at the National Reactor Testing Station by Argonne National Laboratory. The first to explore fissionable fuel breeding and prove it to be technically feasible, the EBR generated about 250 kw of electric power.

Since 1951, other reactors have become operational: the Materials Testing Reactor, the Homogeneous Reactor Experiment, the Submarine Thermal Reactor (STR), the Submarine Intermediate Reactor (SIR), the North Carolina State Reactor (homogeneous water boiler), the Savannah River Reactors, and the first of the North American Aviation Reactors.

Two recent types of reactors are the boiling-water reactor being developed at the Argonne National Laboratory, and its direct descendant, the 180,000-kw G-E dual-cycle reactor being developed for the Commonwealth Edison Company and a group of associates. Financed entirely by private industry, the dual-cycle reactor is noteworthy for its advanced technical conception.

The conclusion of this chronology leads to an apparent question: During the 12 years of building more than 30 different types of reactors, how much new technology was developed and what new scientific discoveries were made? Nuclear physics stands out as one important area benefiting from the reactor business.

### NUCLEAR PHYSICS

The fundamental physics of the nuclear chain reaction worked out in 1941 and 1942 remains almost unchanged. The many advances and new discoveries that have arisen in the broad field of nuclear physics resulted more from continued research into the basic nature of the nucleus than from reactor development and technology.

Reactor technology and science have led to much measurement of cross sections, many elaborate mathematical treatments of the reactor equations, and discovery of new and extremely interesting nuclei—such as xenon 135 with its colossal absorption cross section that almost blocked the first Hanford reactors. Knowledge of the numbers and origins of delayed neutrons that follow fission has been increased. And some new elements, through No. 100, have been created, particularly by Seaborg and his co-workers. Even with these developments, reactor physics today would be much the same to the physicist of 10 or 11 years ago.

Throughout reactor history, one particular characteristic of reactor physics has remained constant: Essentially, it's impossible to calculate with sufficient accuracy all the desired characteristics of a new type of nuclear reactor, making experimentation unavoidable. Thus critical experiments—one type of nuclear reactor experiments—are an integral part of any serious reactor design and development installation.

In the art of shielding, notable advances permit shields of much lighter weight than would have been necessary for the same reactor in 1943 or 1944. These advances, however, have come not as a result of ever more refined and abstruse theoretical work but from direct, practical, experimental measurements of the shielding effectiveness of various materials and combinations.

One interesting concept, the divided shield, resulted from attempts to find lightweight shielding systems, particularly for mobile power plants such as those used in aircraft. First recorded in an official report by the North American Aviation Company in 1948, and independently rediscovered shortly thereafter by the Nuclear Energy for Propulsion of Aircraft (NEPA) project at Oak Ridge, this conception has been extensively developed by the various groups working on aircraft nuclear propulsion. The divided shield is so named because a portion of the shielding is placed around the reactor proper, the remainder around personnel. The combined weight of the two shields is generally less than the weight of a single shield thick enough to safely reduce the reactor radiation.

### ENGINEERING TECHNOLOGY

Although you hear much about the new engineering techniques that either have been or must be developed in nuclear-energy exploitation, a critical look would indicate otherwise. For the only new basic engineering technology emerging as a result of nuclear reactors is that of heat transfer in liquid metals and in boiling-water systems. While reactor engineers have been resourceful and inventive, they have not had to develop other basic new technology.

Confronting them also is the interesting problem of temperature and velocity distribution in a fluid film where heat generation occurs while the fluid flows through a duct or other container. Such a problem might be encountered, for example, in certain homogeneous reactors. And in such a system it seems theoretically possible to cause overheating of the container wall even in the absence of heat generation or transmission through it and in spite of the bulk liquid temperature being held to a safe level.

Some thermal-stress problems peculiar to situations where heat develops in a stressed member also arose and were solved. But on the whole, little original basic engineering technology has been developed. Indeed, an engineering student desiring to train for work in the field of nuclear energy would do well to choose his curriculum from among basic engineering fundamentals, leaving those peculiar to nuclear energy until later.

### CONTROLS AND INSTRUMENTATION

To the uninitiated, the subject of reactor control can be interesting though sometimes slightly frightening. You might logically expect a number of unique problems to have arisen that would require new technological developments. Although a flood of new instruments for the detection, measurement, and

control of nuclear radiation of various types has been developed recently, they are not basically new, with one exception: the scintillation counter in which the interaction of a quantum of radiation with a crystal or other material causes the emission of a flash of light in the visible spectrum. Indeed, many of the instruments use electronic circuits that were developed during World War II, without any subsequent improvement. The instrumentation field, however, has seen considerable improvement in the performance characteristics of available instruments, particularly in such characteristics as response time, dead time, and reliability. Also, many small improvements in certain features of operational convenience make today's instruments much better than those of the early days.

Probably the most significant single development in the field of reactor control was the one carried out in 1953 by the Argonne National Laboratory at the National Reactor Testing Station. For many years, and even prior to the first chain reaction, it had been suggested that a reactor which is both cooled and moderated by water could be made self-controlling if the water were allowed to boil. In such a system, if the reactor power starts to rise, the water boils more vigorously and naturally in the process of boiling a part of it becomes steam. Because this tends to reduce reactivity, it would hold the reactor power at a more or less constant level. For years this concept was discussed theoretically and rejected on the grounds that resultant fluctuations would make the reactor unstable.

In 1953 the Oak Ridge National Laboratory carried out a short series of experiments showing that, over a limited range of conditions at least, boiling did not produce divergent instability in the reactor. Later, the Argonne National Laboratory constructed a small water-moderated reactor and forced it to run away—intentionally increasing its reactivity abruptly and allowing the power to rise as high as it would. When the power had risen to a sufficiently high value, the boiling caused the steam to be ejected, and the reactor shut itself down without damage to fuel elements and without the release of fission products. In other experiments in this same apparatus, the reactor was allowed to boil steadily, producing steam much as a well-behaved boiler, thus exorcising the ghost of divergent instability that is due to boiling. But superstitions of this kind even in a business as new and presumably as free of tradition as reactor development will creep in.

Moreover, engineers are gradually becoming more sophisticated in evaluating the hazards attendant upon the operation of a reactor. The AEC has established an advisory committee on reactor safeguards to examine new reactor designs for their possible harmful effects on people or things in the vicinity of their installation. Such evaluations tend to err greatly on the side of conservatism. But more critical judgments are becoming possible all the time because, as the number of reactors have increased, there have been a very few unexpected power excursions, or surges. Never have they produced harmful effects beyond the immediate vicinity of the reactor, indicating that hazard-evaluation methods have been conservative.

### MATERIALS

The really significant technological advances that have been made in the nuclear energy field occurred in the general area of materials technology—chemistry, metallurgy, ceramics, and the effects of radiation on materials. This is not surprising, for customarily the engineer and the physicist first design a reactor and then complain bitterly if the materials man is unable to immediately supply materials of exactly the properties required.

Some of the major accomplishments in the materials field that resulted from the development of nuclear reactors include the examples that follow.

After several years of intensive reactor operation at Hanford, it appeared that it might be necessary to remove the reactors from service because of the harmful effects on reactor materials. This posed a serious and entirely new problem that was attacked with vigor, perseverance, and intelligence by GE's scientists and engineers at Hanford together with their colleagues at a number of other installations. Result: greatly prolonged lives of the reactors.

A thorny metallurgical problem arose in the early history of the Hanford reactors. The apparently simple and trivial operation of putting a protective aluminum can around the uranium slugs turned out to be the most difficult single technical problem encountered. Entirely new standards of reliability were found necessary. Consequently, many highly refined techniques were discovered, but no new basic technology was acquired.

The field of metallurgy yielded two more interesting examples. Shortly after World War II, beryllium was structurally one of the world's poorest materials. Brittle and nonuniform, it apparently could be worked only by grinding. Unfortunately, this operation produced powerfully toxic beryllium dust, and several near casualties resulted before necessary precautions were understood. In spite of these deficiencies, beryllium was destined to be an important reactor material. For this metal is an excellent moderator, having a low atomic weight, good scattering cross section, and small absorption cross section for neutrons. During a three-year period, beryllium was converted into a workable metal. And today it can be machined, forged, tapped, and handled in much the same way as the more common metals. Now, in addition to higher purity and uniformity, beryllium has increased mechanical strength and toughness.

Zirconium—a metal of good corrosion resistance and excellent nuclear properties—seemed the favored material to use in the reactor of the STR program. However, zirconium as then produced contained a small percentage of hafnium that not only has a large neutron absorption cross section but also is extremely difficult to separate from zirconium. AEC contractors undertook this problem, quickly producing a hafnium-free zirconium of high quality.

The progress made in the handling of liquid metals can be cited as an example of successful materials technology. The liquid metals in general, and the alkali metals in particular, have superior heat-transfer properties. Other liquid metals, such as bismuth or lead-bismuth alloys, also have fine heat-transfer properties plus other characteristics that command the attention of reactor designers. However, the problem of containing these liquids, particularly at high temperatures, proved to be a substantial barrier to their direct use in reactors. Here again the chemists and metallurgists of the contractors associated with the AEC, foremost in the group being those at the Knolls Atomic Power Laboratory, attacked the problem. They learned that minute traces of various impurities caused corrosion of container materials for the alkali metals, particularly when accelerated enormously at high temperature. By painstaking removal of these impurities, the metals can be contained at high temperatures for extremenly long periods. Concurrently, pumps of both moving rotor and magnetic types were developed for pumping liquid metals at high temperatures.

High-temperature materials in general have benefited greatly from the stimulus of the reactor development program. For example, a new brazing alloy suitable for joining various nickel-chromium-iron alloys does not contain boron, making it applicable to nuclear reactors. (The older and less satisfactory alloy contained boron.) This material, developed by GE's Aircraft Nuclear Propulsion Department, is finding use outside the reactor field.

It may be asked whether any new technology arose from work on radiation effects on such materials as lubricants, electric insulators, and elastomers. Sometimes, new products have resulted: crosslinked polyethylene owes its strength to irradiation after manufacture. Generally speaking, however, radiation-damage work has been confined to searching out those materials not adversely affected in large degree. Thus a substantial body of information is accumulating on the susceptibilities of different materials to various types and amounts of radiation, but this would hardly be called a new technology. Other instances can be cited: sometimes the addition of chemical inhibitors can reduce radiation damage to organic materials, but this seems to be the exception.

These are only the most obvious technological contributions of the initial period of development. And now the 1954 revisions of the Atomic Energy Act open the field for a more normal exercise of individual initiative, competition, inventiveness, and responsibility. In the years to come, these factors will be extremely valuable, materializing in increased research and development programs for the constructive use of atomic energy. Interesting and dramatic as the past years have been for a relative few, they will hardly compare with those of the future for all.

**The second of ten FORREST SHERMAN-class destroyers, USS JOHN PAUL JONES (DD 932), has been launched. The 418-foot vessel mounts the Navy's latest developments in electronics, gunnery, navigational, engineering and anti-submarine equipment, as well as the newest comfort features for her 350-man crew.**

REAR ADMIRAL HYMAN G. RICKOVER, U. S. NAVY

# *ENGINEERING AND SCIENTIFIC EDUCATION*

**THE AUTHOR**

*In the February 1956 issue of the* JOURNAL, *we published "Nuclear Power and the Navy"—a speech which Admiral Rickover made before the San Francisco Council of the Navy League. In obtaining permission to publish that paper we encountered "Engineering and Scientific Education." These are remarks which Admiral Rickover made before the Thomas Alva Edison Foundation, Inc. in November 1955. Because of the author's intimate experience, in his dual role of Chief of the Naval Reactor Branch, Division of Reactor Development, U. S. Atomic Energy Commission and Assistant Chief of the Bureau of Ships for Nuclear Propulsion, with the problems of finding engineering and scientific personnel, we are publishing this paper as a contribution to the national campaign which is designed to improve the supply of engineers and scientists.*

For the last eight years my work has been in the field of nuclear power. In dealing with the problems involved in developing this new source of energy I have found them to be but one facet of a much larger problem—how to provide the trained men and women to maintain the momentum of our rapidly expanding technical civilization. You are all aware that our explosive population growth has placed a tremendous strain on the resources—human and material—of our educational institutions. There are just not enough good teachers and schoolrooms to give each child the opportunity to develop his capabilities to the fullest.

I consider the present crisis in education as grave a problem as any that faces our country today. Unless it is dealt with promptly and effectively the machinery which sustains our level of material prosperity and political power will begin to slow down and we will be in danger of losing the cold war by default. Let me illustrate this with a few figures:

First, the United States has doubled its population in the past fifty years and is expected to double it again by the end of the century.

Second, with only seven per cent of the world's population and eight per cent of the land area, the United States is today responsible for more than half the world's production.

Third, to maintain our relative position in the world economy and to preserve our high standard of living, American industry must—ten years from now—produce forty per cent more than it does today.

The use of electric power, for example, is expected to quadruple in the next twenty-five years. Or take minerals and most mineral fuels: the United States has used up more of these in the last thirty years than the entire world did in all of history before 1914. A similar growth in consumption in the next thirty years cannot occur unless we make profound changes in technology.

Our accelerated increase in production over the past century has been due to the efforts of but a small number of companies. Only one per cent of all the businesses in existence a hundred years ago are still alive today. And in a recent study by the Brooking Institution it was shown that only thirty-eight of the one hundred largest industrial companies existing in 1909 are still in business today. The companies which survived are those which have been willing to experiment, to take risks, to innovate, to break precedent. Their managements have anticipated and helped to bring about the very changes which caused their less astute or less courageous competitors to slip back. These companies hold their place in a world of change. The top is a slippery place.

The same holds true for nations; like industrial organizations, they will decline if they are not continually alert to the needs of the future. The law of life for industrial organizations and for nations is the same: "adapt or perish." The industrial, and hence the politcial power of nations is dependent in large part on their scientific and engineering professions, and these in turn depend on a continuous inflow of capable and well-trained individuals. In other words, a nation progresses or falls back in the race for survival to the degree that it succeeds or fails to afford each individual citizen the maximum opportunity for education and training.

An essential function of leadership, in the government of nations as in the management of industries, is to plan for the future. What we do today was largely determined for us by the vision and action of those who preceded us. Likewise, tomorrow's events will depend on what we plan and do today—on the wisdom we use in planning for the future. Perhaps the most insidious weakness a nation can have is the belief, fostered by propaganda of one kind or another, that it can do everything better than other people. We in this country are subjected to this kind of propaganda in various media—such as the slick advertisements of magazines—week upon week, month upon month. We overlook what we do not hear much about, especially if it is unpleasant.

One of the unpleasant facts which has but recently been mentioned is that in the field of scientific and engineering education our main competitor—Russia—is speedily passing us. According to the best estimates, the United States now has about 800,000 engineers and scientists—Russia 650,000. Disturbing as this is, it is insignificant as against the rate with which she is increasing her engineering and scientific talent compared with us. In 1954 she graduated more than 50,000 engineers and scientists; we graduated 23,000. Mr. Allen Dulles, the Director of our Central Intelligence Agency, has stated that between 1950 and 1960 Soviet Russia will have graduated 1,200,000 scientists and engineers, compared with 900,000 in the United States in our present program. Thus by 1960 it is estimated she will have more engineers and scientists than we; moreover, the rate of attrition in Russia is lower than ours because of lower age.

Some may argue that Russian engineers are not technically as well trained as ours. This is not the case. It is true that they are trained in engineering exclusively and at the cost of their general education. Further, their engineering training is confined to narrow specializations. This is so because the Soviet educational philosophy is based on the premise that the purpose of education is to train the individual for the particular purpose the state requires.

You know what kind of a job the Russians have done on jet engines, radar, long-range bombers, and atomic weapons. Their industrial production has quadrupled in the last fifteen years.

The Russian approach to education is a total approach. They are educating as many women as men, and women constitute one-half of the total in the professions. In contrast, in the United States this is but a fraction of one per cent. Can we continue to neglect so large a potential of trained personnel?

While our mass production system will permit us, for the time being, to build more things faster than Russia, their engineers may soon, by their very numbers, invent better machines. In rate of progress they are, in fact, already ahead of us. We must not take for granted our present technological leadership.

There are some who believe that the United States is not even graduating enough trained people merely to sustain our present rate of technical expansion beyond the year 1970. What is certain is that unless the number of our scientists and engineers increases at an accelerated rate our economy will be in serious trouble for lack of technological nourishment, because our pool of graduate engineers is the source from which arise nearly all our technological advances from jet engines and nylon, to earth satellites, atomic power, and intercontinental missiles.

In light of these facts the present Soviet peace offensive makes a great deal of sense to the Russians. Recently Mr. Khrushchev said: "We don't have to fight. Let us have peaceful competition and we will show you where the truth lies , . . Victory is ours."

Can we in the United States permit this challenge to stand?

America's present educational crisis is not only one of quantity—i.e., not enough engineers and scientists being graduated each year—but also one of quality. And this is a serious matter, for in the contest with Russia we must depend on greater human quality, since we cannot match her manpower in numbers.

Our primary and secondary schools have recently come in for much criticism for not doing a good job. Actually, the average high school graduate of today is better trained than the one of seventy-five years ago—which should not surprise us since today's school year is twice as long as that of 1870; the proportion of teachers to pupils is greater; and—even taking into account the changed value of the dollar—we spend nine times as much per pupil today as we did in 1870. We have thus a situation where the child goes to school twice as long, costs us nine times as much to educate, but gets only a little better education than he was getting eighty-five years ago.

Unsatisfactory as this may be, the real issue is not whether the present-day pupil compares favorably with the pupil of 1870 but whether he is adequately trained for the demands of today's society. I submit that he is not.

I say this on the basis of study, intuition, and the experience I have gained from interviewing more than one thousand college graduates over the past ten years.

My experience in selecting people may have some relevance for other engineers because the design and development of nuclear power plants is extremely difficult. It encompasses the most advanced scientific and engineering concepts in physics, mathematics, chemistry, metallurgy, electrical engineering, electronics, and mechanical engineering. The problems

we face in nuclear power plants are indicative of what all branches of engineering will soon have to face.

The single most important thing I have learned from these interviews is that all but a small number of the young college graduates lack proper motivation. Some of them consider their degree merely as a ticket to a job, and a pass for security. They use the college as a "service station."

This desire for security in terms of money, rather than in opportunity for self-improvement is hard to understand in a society where security is so readily available.

Another important point that has been made clear to me in interviewing young graduates is that they know many facts—but they have not learned many principles. Principles are more important than facts and far more difficult to master. But once a principle is learned it becomes a part of one, and is never lost. The facts we learn are soon forgotten and their meaning changes with time. A trained man knows how to answer questions. An educated man knows that questions are worth asking.

My concept of a good engineering course is one in which the student learns the principles of mathematics, of physics, of mechanics, of electricity, of metallurgy, and of chemistry. A thorough understanding of these leads easily to handling the facts associated with them.

I do not believe that "practical stuff" should be or can be properly taught in a university. The reason is easy to see. Nearly all college textbooks are several years behind current industrial practice. Furthermore, they are written by men who do not have the latest "practical" information, so that the texts are obsolete even while they are being written.

The employer who wants a "practical" engineering graduate is simply hiring a man who knows how to make the same mistakes that have been made in his plant for the past ten to fifteen years.

The failure in education is not the fault of the educators alone. It is the fault of all of us in not recognizing the impact of the Twentieth Century scientific revolution and taking the necessary measures in time.

I have tried to give you my view of some of the problems that face us in engineering education. What can we do about them?

*First,* we must see to it that every young man and woman who is qualified obtains a college education. Today less than half of those capable of acquiring a college degree enter college. Sixty per cent of the best students graduating from high school do not go to college. This is a tremendous loss of talent amounting to 250,000 students each year. And nearly half of all those who do start college do not graduate. For every high school graduate who eventually earns a doctoral degree there are twenty-five others who have the intellectual ability to achieve that degree, but do not. We simply cannot afford a waste such as this.

*Second,* we must increase the funds for education. The United States is spending about two and a half per cent of the national income on education. In contrast we spend more than four per cent on recreation. We spend more money for comic books than for all textbooks used in our elementary and high schools. In 1951 the amount spent for advertising was $199 for every family in the United States, but the amount spent for primary and secondary education was $152 per household. This means that our national outlay for the education of citizens was substantially less than our expenditures for the education of consumers.

It may amuse you to know that in a recent year the United States home permanent wave industry budgeted for research into ways of improving the looks of human hair a sum amounting to two cents per United States (female) capita. The whole nation meanwhile was spending only three cents per capita for research into the distressing things that go on inside the human head.

*Third,* from what I read in the papers we seem to be more concerned with expenditures for school buildings than for spending money to obtain better teachers. Schools can be constructed in two years or less, but it takes four years to train an elementary or high school teacher, and seven to eight years to train a college professor. Our school buildings may be the best in the world, but can we say the same of our teachers? I do not mean to imply that we should not have the best school buildings, but perhaps our children would be better off with fewer buildings but with the best teachers it is possible to obtain. We plan to spend twenty-five billion dollars in the next ten years on school buildings. What amount are we prepared to spend for assuring better teachers for these schools?

The real question is, "Can we afford not to spend enough for such assurance?"

This leads me to the questions of the salaries we pay teachers. Compared to other professions there has been a considerable drop in their purchasing power, particularly for those at the highest professional levels. The deterioration at the top is so great that it has affected the attractiveness of the academic career as compared to other professions.

In any profession, and particularly in the teaching profession, there are dedicated people who will work under adverse conditions and at low pay. But we must not delude ourselves that the answer to our dilemma lies solely in dedicated people. There will never be enough of these. We are not entitled to educate our children on the philanthropy of our teachers. Whether we like it or not, in the culture which exists in the United States today the desirability of a given occupation is measured largely in terms of salary. As a rule the better people are attracted to the higher paying professions. This explains why the ablest young men and women are turning away from teaching even though numerous scholarships and fellowships are available. No such recruitment problem exists, for example, in medicine or in law. These have no lack of applicants; in fact many are turned away.

When the income of teachers rises to the point

where it competes with other professions, it will attract the right kind of people.

Therefore, I submit that an immediate step in solving our educational problem is to increase salaries drastically. It little matters that some teachers will be overpaid. The low salaries paid for the past fifty years have served to attract to the teaching profession many who are not really qualified. It will profit us very little to spend millions of dollars on scholarships and then place the students under incompetent. teachers. Increasing salaries is the surest way to attract more competent men and women over the long run. Further, when salaries are increased it will be possible to base advancement on performance, and not on the basis of time served.

Unless we quickly remedy the present treatment of our teaching and scholarly resources we will inevitably have morally and intellectually incompetent teaching staffs. Eventually the bright young man will sacrifice his desire to teach in favor of an adequate standard of comfort, decency, and security for his family. The movement away from teaching has actually begun and it looks as though it will continue at an increasingly rapid rate.

We all know of the nationwide shortage of elementary and high school teachers. What is not evident is the real meaning of this shortage, because very few classrooms are ever closed because a teacher is lost. What happens is that teaching standards are lowered or the class size is raised. Both of these accommodations are already taking place at a growing rate. When a teacher with the desired qualifications is not available, someone with lesser qualifications is hired. The teacher then becomes, in effect, a "baby sitter."

The result of this niggardly payment of our teachers—of those upon whom we depend to transmit our culture and our civilization—is to commit a fraud on our children. If the children were as astute as their elders supposedly are they would say: "I'm sorry, but I'm not ever going to be ten years old again. Can't you afford to give me good teachers now?" '

Another thing we can do is to increase the length of the school year. The present school year is based on the requirements of an agricultural economy where the children had to help on the farm. True, the actual number of days at school now averages about 180 as compared with 90 days about 80 years ago. But, as you well know from your own experience, and from what your children tell you, many of these 180 days are wasted. With the great and geometric advance in knowledge since the turn of the century, can we afford to have our children devote less than half their available days to elementary schooling? Students in Europe, including Russia, attend school six days a week instead of five, and their vacation period is about two-thirds of ours.

There is no longer a sufficient number of years left during youth to develop properly educated men and women. And we cannot keep them in school too long after they reach the age of twenty-two or twenty-three because it is then time for them to face the problems of the world. So it is to the earlier years that we must look for added learning. This problem has become particularly acute due to universal military training.

Many of you occupy responsible positions in industry, and you know that the great increase in our productive capacity comes from the optimum use of people and facilities. Some of the problems of education, particularly those concerned with administration, are susceptible of solution by the same methods we use in industry. Industry cannot operate effectively on a 180-day year. Why should we think our schools can?

Increasing the length of the school year, say to 210 days, would be the equivalent of making two additional years available before college.

If to these two years we added better teaching, better school administration, and better use of school facilities, it is quite possible that by the time a young man reached the age of eighteen he could have completed the equivalent of the present day college course. This is not as farfetched as it may sound. Something close to this has been achieved in Europe.

Another important thing to be done is to make it possible for every gifted student to advance as rapidly as he is able to. It may be impossible for us to compete with Russia in the number of trained people but we must excel in the quality of our trained people. To accomplish this requires a drastic change in our attitude toward our primary and secondary schools—particularly our high schools. Up to World War I the high school was intended as a preparatory school for those who desired to continue on to college or university. The courses were organized on this basis and they did a pretty good job, considering the cultural and scientific climate of the time.

But the high school of today is no longer a place whose primary purpose is to prepare students for college. Instead, its purpose has proliferated into providing educational, occupational, civic, and cultural training for every child.

In this time of acute teacher shortage in our schools we might well consider relieving them of the problems which could just as well be taken care of in the home or by other activities. Under pressure from various groups, courses are being given whose educational value is questionable. Nearly half of our high schools offer little or no instruction in physics, chemistry, or in mathematics beyond introductory algebra. The percentage of high school pupils who today study scientific subjects is indicative of this:

| | 1900 | 1950 |
|---|---|---|
| Physics | 23 | 4 |
| Chemistry | 10 | 7 |
| Algebra | 52 | 27 |
| Geometry | 27 | 13 |

The high schools have been required to arrange the necessary curriculum to take care of the average boy or girl. For many children the school makes up for what they cannot obtain at home; and, in some cases, it takes the place of the home. The ones who suffer are the gifted children. Some parents, those who can afford to, send their children to private schools.

Whether or not these are really better than our public schools is a moot question. Certainly it is not altogether desirable to have children, during their impressionable years, associate only with those who have the same economic background.

A partial solution to the high school problem lies in setting up two different kinds of schools, one having higher standards than the other. There can be no valid objection to this because boys and girls with the necessary ability could go to the more difficult school. True democracy does not require of us that we hold back the qualified; it does require that we give each individual the opportunity to develop his talents to the fullest.

There is, however, a current of educational thought which is opposed to special treatment of gifted children. It is claimed that there are too many difficulties and injustices involved in recognizing ability at an early age, so that children of all abilities must be educated in a common manner. It is also claimed that educational grouping of this sort leads to or accentuates social stratification, and is, therefore undemocratic.

Neither of these arguments will bear critical examination. If it is considered democratic to give special care to our retarded children, as we should and must, why should it not likewise be considered democratic to help our brightest children. There are many things which are pure gifts and which we cannot acquire even by the greatest application: they are endowments granted to us by God. Among these gifts are creative artistic talents, profound sensitivity to art, music or literature, philosophical power, and scientific or engineering intuition.

Every outstanding scientist or engineer is in his own way an artist. That is why he is able to reach out into the unknown and grasp a new truth which remains invisible to others.

This is the reason we must seek out and cultivate our gifted children, for it is from their ranks that creative ideas will come.

I have spoken of these major methods by which our educational potential can be improved: increasing the length of the school year together with better school administration; making sure that gifted children are afforded every opportunity; and obtaining enough good teachers.

Here are the unprecedented educational problems we now face: Elementary school enrollment has risen from 20 million in the 1940's to 29 million today, and is expected to reach 34 million in 1960. High school enrollment will increase from 7 million today to about 12 million in fifteen years. But the severest impact will be felt by the colleges and universities where the attendance will increase from about 2½ million today to between 5 and 7 million between the next 10 to 15 years.

To maintain the present pupil-teacher ratio the elementary and high schools will have to enlarge their teaching staffs by 500,000 in the next ten years; this is a greater increase than took place in the previous thirty-five years. But to achieve a net increase of 500,000, three times that many will have to be recruited to take care of those who leave to get married, to take other jobs, or to retire. And the colleges and universities will have to add more teachers in the next fifteen years than they have in all their previous history.

But faced with this formidable and unprecedented situation, we start with a present shortage of 140,000 qualified teachers. If the nation's schools are to be adequately staffed during the next ten years more than half of the college graduates during that period will have to enter the teaching profession. But at present only one-fifth of the college graduates become teachers.

Our difficulty arises from the fact that we are not living in a static society, nor do we have a static population. We are faced with a national problem of the first magnitude and a major and over-riding effort by all of us is necessary—the federal government, the state and city governments, the schools, industry, and other private organizations. Because we have not been mindful of this situation does not mean that others have been equally unmindful. The meaning of what the Russians have been doing in education now becomes plain.

A partial solution and one which could be immediately effective is to enlist the aid of industry. Why cannot the scientists and the engineers from industry be given sabbatical leave to teach in our schools? The very shortage of college graduates and many of our educational problems have been created by the vastly increased requirements of industry. In 1900 the ratio of engineers to other workers was one in three hundred; today it is one in sixty—and in highly advanced industries it has already reached the figure of one for about every twenty workers.

Industry is today short more than 40,000 engineers and will require a minimum input of 30,000 for many years to come. The only serious attempt made by industry to solve this problem has been to offer considerably higher salaries to young college graduates. This has resulted in an unhealthy situation where the small number of graduates are being sought after by many organizations. Recently, at one college, the same 200 members of the graduating class were interviewed by representatives of nearly 500 companies. This is not recruitment; it is inflation. We have learned in the case of goods that inflation can only be solved by greater production; this is true of college graduates as well. There is danger to the young graduates in being sought after so avidly. Success is too easily achieved, and he gains it so quickly and so easily that he has had no time to learn the humility to handle success, or even to realize that he will need humility.

It is not farfetched to expect industry to help carry this social obligation. In present day America the business corporation is not a business device alone—it has become a social institution and has acquired the obligations inherent in this concept.

We have always recognized a duality in our schools: federal and local support; public and private

support. Industrial support of schools fits into this duality.

It has also been characteristic of our people that when a social need arose which government was not able to take care of, groups of citizens have joined together to help.

Specifically, I suggest that, at their own expense, industrial organizations make available their scientists and engineers for one-year periods to teach in our high schools, colleges, and universities. The cost of this will be more than repaid by the larger number and better trained students who will soon be available.

Another thing industry can do is to help finance education. This has already been started by some incorporations in providing scholarships and other aid. I suggest that financial contributions to education rather than scholarships be made, but on a considerably larger scale than is presently the case, perhaps as a percentage of gross sales. These funds might be assigned for distribution to central groups of men not associated directly with industry or with the schools. This will eliminate any possibility of industry being accused of influencing education or the schools of being self-seeking.

The use of manpower and funds by industry in this manner could be considered as a legitimate operating expense required for the future good of the business.

Similar contributions by labor unions would also be appropriate.

There are a number of aspects connected with this proposal which I would like to discuss at greater length, but which time does not permit. There is the possibility of using the funds so contributed for the establishing, staffing, and operating of new schools. There is also the possibility that scientists and engineers of each community, as part of a definite company plan, could act as counselors for one or more high school students devoting a part of their time to helping them to become interested and proficient in scientific and engineering subjects. They could also take over the leadership of the various after-school clubs in science, radio, mathematics, etc., thus relieving the teachers of this dutv.

The United States, if it is to succeed in its role of world leadership, must produce citizens who have the wisdom, the vision, and the knowledge to grapple successfully with world problems; citizens who can see critically through conventional values and who are able to subject to principle and to reason all claims to power.

In the conditions of modern life the rule is absolute, the race which does not value trained intelligence is lost. It will matter little what other excellences our educational institutions possess if they neglect to recognize and to foster high ability wherever it is found.

The task of ensuring that every youth in our land is helped to his highest intellectual growth is a formidable one. This task arises not alone from the military situation posed by Russia, but also from the realities of the rapidly spiralling scientific revolution. We are faced with a fateful challenge. The way we, today, meet it, will determine the future of our Country. We must not let it be said by future generations that we used our intellectual and moral capital without replacing it.

Only by an educational system strengthened, not only in its members and its organization, but in its sense of purpose can we hope to meet the obligations which today's events place upon us. And only if we meet them can we create in our society the kind of leadership without which we cannot hope to meet the responsibilities and the possibilities that our time has opened before us.

Navy WAVES comprised 55 per cent of the military personnel in the Navy Department in Washington, D.C., during World War II.

# *HOW TO WELD HIGH-PRESSURE VESSELS WITH AUTOMATICS*

**ACKNOWLEDGEMENT**

*This paper was presented at the American Welding Society's 1955 Fall Meeting, and was published in the December, 1955, edition of "The Welding Journal." The author is Wilmer W. Weber, Welding Engineer of the Pfaudler Company, Rochester, New York.*

## INTRODUCTION

A SURPRISING RANGE of welding jobs are performed at our plant by submerged arc automatics. Typically, quality is higher and costs far lower than manual welds.

All-welded equipment includes high-pressure reactors, vats, tanks, columns and a variety of custom-built processing machinery. Both internal and external welds are performed automatically on either circumferential or longitudinal seams.

Work dimensions are equally varied. Vessels range in diameter from 3 to 13 ft. and may be up to 50 ft. long. Plate thicknesses vary from ¼ to 1¾ in., widths from 36 to 140 in. and lengths from 7 to 45 ft.

The most frequently used material is ASTM Grade 285B flange quality steel, but we also handle a dozen or more alloys on our automatics regularly. Despite these variations, weld quality has to be tops because most of the vessels are glassed after welding is completed to withstand corrosion of chemicals. Flawless welds are a prime requisite for an impervious glass or alloy surface and for proper performance of the vessel. Furthermore, internal pressures range from full vacuum up to 225 psi.

Company engineers have been surprised at the variety of jobs that can best be handled by automatics. Problems? Definitely. And we surely don't have all the answers. But since we started using this process 14 years ago, we've uncovered a few which may be helpful to the reader.

The key points to consider for good results with submerged arc welding are selection of the right equipment, joint design, preparation of edges, welding procedure specifications and quality control. As a basis for our consideration of these factors, let's review how submerged-arc welding equipment operates.

## EXPLANATION OF PROCESS

The submerged-arc welding process, or hidden arc process as it is sometimes called, was relatively unknown 14 years ago. It was during the Second World War that speed-up in our welding processes was started to expedite production. This process really came into its own at that time and today is used widely in industry.

The submerged-arc welding process is just what its name implies. The arc is completely covered by a blanket of granulated mineral material called flux, and cannot be seen. As the arc between the electrode and the workpiece generates heat, molten metal is deposited from the electrode under the blanket of flux. A portion of this flux becomes molten and solidifies on the surface of the weld metal. In this manner the deposited weld metal is completely protected from the atmosphere and is practically hydrogen free. Because the arc is completely hidden, the operator needs no helmet or glasses to protect him from arc flashes or spatter. The process is also practically smoke free and the presence of obnoxious fumes is reduced to a minimum.

The equipment needed for the submerged-arc process includes a wire-feeding mechanism, a current control station, power supply, a flux feeding device and a flux recovery unit.

Normally, a bare coiled wire is used as the electrode which is fed automatically into the weld puddle by a variable speed motor which is controlled either electronically or by straight voltage exciter controlled equipment. Coated coiled wire or bare wire in straight lengths are also used in other applications. Power supply can be either ac or dc and should have ample capacity for long duty cycles at high current densities.

Amperage, voltage, diameter of wire and relative motion between the workpiece and the automatic welding head all play an important part in determining the appearance, penetration and quality of the weld. Since the arc or molten weld metal cannot be seen, methods of guiding the automatic head must be devised by mechanical indicators. A projected spotlight beam or mechanical pointer will guide the electrode in the proper relationship to the joint. This is very important to the process and the author will relate to it later on.

### SELECTION OF EQUIPMENT

Before automatic equipment is purchased, a careful survey should be made of the job it is to perform to determine:

A. Materials to be welded
B. Size and shape of product
C. Production rates necessary
D. Accessibility of the joints
E. Flexibility of equipment
F. Comparative cost
G. Maintenance required

Various types of automatic welding equipment commercially available today make it possible to select the optimum apparatus for the job. We find electronic controlled equipment and d-c motor generator exciter controlled equipment the best combinations. Both types weld almost identically; however, there is a major difference in initial cost and maintenance.

Some types of equipment will take any size wire from 3/32 in. diameter up to and including ¼ in. diameter without necessitating any disassembly of the wire-feeding mechanism. Others require a change of electrode drive rollers, contact jaws, wire guides, etc. Changes of wire sizes are often necessary due to varying material thicknesses and welding procedures and so should be considered in the selection of automatic equipment to assure change-over without excessive downtime.

Selection of positioning equipment to accommodate the product should also be considered at the same time because motion between the welding head and workpiece is of the utmost importance.

In welding pressure vessels, it is essential that the travel carriage and turning rolls be controlled from the operator's station. Any variance in fit or out-of-roundness can then be remedied by either slowing down or speeding up the workpiece to obtain the required weld deposit. With such controls, the operator can move other seams on the vessel into position and weld them without leaving his station.

The welding head support should be constructed to give the maximum versatility and also be rigid enough to prevent any whipping or vibration because such motion will seriously affect the weld.

To assure adequate versatility of the welding head manipulator, the welding engineer must consider all welding aspects of the work which may be required. The author does not believe it is wise to have each station so constructed that it is limited to one set procedure. At a very slight additional cost each station can be made to weld more than one job and thus save many expensive production hours. Also, in the event of a breakdown of the automatic equipment at one station, another station with this flexibility can avoid stoppage of production.

The author would like to add one note of caution to the prospective purchasers of this type of equipment. In the event you have the design of such equipment done by outside engineering firms, be sure that your welding engineer studies and analyzes very carefully the proposed designs. Too often equipment of this type is overdesigned which not only greatly increases the initial cost, but is more complicated to maintain and operate. Keep the equipment as simple as possible.

### EDGE PREPARATION FOR WELDING

Preparation of edges of large diameter pressure vessels to be welded is very critical, and special attention must be given to this phase of the fabrication. Plate sizes are usually so large that machining of the bevels is practically out of the question costwise. Therefore, in most cases the edges are prepared for welding by flame cutting while the plate is flat. Due to the waviness of plates, floating torches are used to help keep bevels even. Machined bevels, however, are highly desirable and are used in some instances, especially on alloy pressure vessels. A horizontal planer is one of the machines used to bevel straight plates. Multiple hydraulic clamps are necessary to insure flatness during machining.

It is also desirable to have the surfaces adjacent to the flame-cut edges free from any rust or scale, but this presents quite a material handling problem. Therefore, the plates are normally flame cut, rolled and welded without cleaning. While this procedure is not recommended by the author, the expense involved in grit blasting or grinding the flame-cut edges is prohibitive, therefore, we must depend upon the proper filler wire and type of flux to combat welding defects caused by rust or scale.

Heads for pressure vessels are trimmed in almost the same way as the plates. A horizontal boring mill with a floating torch mounted at right angles to the bed is used in beveling a head. This machine can prepare the edge for welding in one pass, which makes a squaring cut and two bevels.

### JOINT DESIGN AND SETUP

Joints for pressure vessels must be designed to make possible welds which will meet operating specifications. Bevels for pressure vessels are in no way different than for nonpressure types. Because of the

high currents used with submerged arc welding, bevels can be kept to the barest minimum; the high currents melt the base metal and in turn less filler metal need be added to the joint.

The most important phase of fabrication is the fit of the courses to the shells and courses to the heads. Due to the large diameter of many vessels, it is virtually impossible to get a uniform fit-up prior to automatic welding. A great variation in fit-up generally produces a weld with high stress concentrations, if not followed by postheat treatment. The finished appearance is also impaired by the irregularity of the weld bead.

It is, therefore, necessary that added precautions be taken at the setup stations to provide a uniform joint for welding. This in turn will pay off at the automatic weld station in quality work, and in time saved in re-welding or multipass work on sections of the welded seams. Joint geometry and relative position of joints on the vessels must also meet all code requirements.

Elaborate fixtures are needed to provide uniform joints. However, due to the high costs involved, many manufacturers are still erecting these vessels by the old turnbuckle and clamp methods.

### WELDING PROCEDURE SPECIFICATIONS

To set up simplified standard welding procedures on pressure vessels poses an almost impossible task. Where a standard line of vessels is built, the problem is not difficult. However, complications do arise in plants where vessels are of different material, stock thickness, diameter and length.

In order to give the automatic welding operator a good welding procedure, it is necessary to include the following information: diameter of electrode, electrode type, flux, amperage-voltage, speed of travel (IPM), number of passes, weld contour or reinforcement and the amount of offset of the electrode on circumferential seams. In order to accomplish this, a separate procedure would have to be issued with each special type of vessel.

Since this may involve considerable time and expense, an average procedure or data sheet can be issued to the operators and they in turn can use this data sheet as a guide to make the proper adjustments of the equipment. After an operator is well versed in the operation of the automatic equipment, he seldom has to consult the data sheet for operating instructions.

When stock thickness is such that a weld from each side can produce a satisfactory weld, the writing of a welding procedure is not too difficult. The welding procedure becomes very difficult where multipass work is necessary because each pass must be numbered and different settings of amperage, voltage and speed of travel on the equipment must be spelled out in the procedure. In the event vessels are of large diameter 10 to 14 ft. and made of light plate stock, ¼ to ½ in., they are usually out-of-round or egg shaped. In cases of this kind we rely solely on the operator's judgment to overcome the condition.

One may ask, "Why bother with procedure at all?" Written procedures give three benefits:

1. The welding operator and foreman has at his fingertips a guide as to speed of travel, amperage, voltage, wire sizes, etc.

2. We can place the responsibility for welding directly with the welding engineers who write the procedure instead of with the operator or supervisor.

3. In welding low-alloy steels the type of filler metal can be specified and not left to the discretion of shop personnel.

The procedure should also specify the relative position of the electrode to the joint. On circumferential seams the electrode must be positioned off center to allow for weld puddle drag. If the electrode is not off the vertical centerline of the vessel far enough, the weld metal will pile up or hump up in the center. Conversely, if the electrode is too far off center, a concave weld will be the result with many attendant defects.

Insufficient penetration is one of the most common sources of weld defects and is usually discernible by small pinholes through the center of the weld. Gas is trapped between the first pass and the second pass and escapes by bubbling up through the solidifying weld metal.

To help in obtaining a uniform joint prior to automatic welding, the joints are inspected after they are tack welded together. In the event openings over 1/16 in. are found, buttering passes with stick electrodes are used to prevent the automatic weld puddle from dropping through. In many cases it is customary to backchip, grind or gouge to solid weld metal to insure a top quality weld.

As the shells or courses are taken off the rolls a fast sealer pass is made on the outside of the shell with Class E-6011 electrodes. This serves two purposes. It holds the shell together while being moved to the automatic welder and secondly it provides a sound backup to prevent burn-through with the automatic welder. After the outside is welded, power turning rolls rotate the shell 180° and the weld is then completed on the inside. This is standard procedure on all longitudinal seam welds.

The circumferential welds are completed in exactly the reverse procedure as the longitudinal welds. Some of the reasons for this reversal are:

1. In the event some sections of the seam need a buttering pass, due to poor fit-up, it is easier and faster for an operator to weld in the interior instead of sitting on top of the vessel or operating from a scaffold.

2. A flatter weld can be obtained on the inside of the vessel which minimizes grinding.

3. A better quality weld is obtained on the interior due to the annealing action of the outside weld.

4. Backchipping or gouging is accomplished with greater ease on the outside.

### QUALITY CONTROL

Quality control is most important during the fabrication and welding of the vessel. Inspectors have

the sole responsibility for either acceptance or rejection of the vessel.

The code to which a vessel is being built determines inspection standards and procedure. Code U-68 specifies X-ray examination of welds. It also requires all weld metal .505 tensile tests, transverse tensile tests and root and face bends. Many customers are gradually turning to less critical codes such as U-69 and the 1952 Code.

To keep welding quality at its best, the Inspection Department is expected periodically to spot X-ray vessels as they progress through the factory, whether the job calls for X-ray or not. This procedure serves a double purpose:

1. Production personnel never know when or what vessel the inspector will spot X-ray. Therefore, foremen are constantly checking their own departments for poor welds and attempt to keep operators performing at their best.

2. This procedure somewhat relieves the inspector of very critical and time-consuming inspection. However, it does not relieve him of total responsibility for the vessel.

It is the duty of the welding inspector to mark any defects he deems necessary to repair. Each welder is required to place his stamp or identification number next to any weld he has made. In this way, the inspector can determine whether the individual operator is complying with preset standards.

When X-ray cannot be used, trepanning is acceptable as an inspection method. This method of inspection, however, is costly and after the hole is welded from which the trepanning was taken, the only means of inspecting the welded trepan section are by dye penetrant, or visually. The author suggests X-ray wherever possible.

## CONCLUSION

Due to the numerous advantages of submerged arc welding, the use of this process for joining metals is increasing daily. Manufacturers are constantly seeking ways to reduce costs, improve operator working conditions, increase production and gain better quality and appearance. One major way of accomplishing this is to eliminate the operator variable by the use of automatic equipment. Automation has definitely entered the field of welding. The automotive industries are taking full advantage of the savings derived from automatic welding setups.

Submerged arc welding of pressure vessels is widely accepted and meets all code requirements. The author recommends it as an excellent process for pressure vessel welding.

**At the Navy guided missile test range, Point Mugu, California, there is a huge $3,000,000 electronic marvel that can perform approximately six million mathematical operations in five minutes, problems that would take an average mathematician 4 years to complete.**

# *PIONEERS IN ELECTRICAL COMMUNICATIONS*

**ACKNOWLEDGEMENT**

*This article appeared in the January, 1956, edition of the "Journal of the Franklin Institute," which edition was a commemorative issue honoring the 250th anniversary of the birth of Benjamin Franklin. The authors are Eligio Perucca, Director of Politecnico di Torino, Italy, and Vittorio Gori, Director of Instituto Superiore delle Poste e Telegrafi, Rome, Italy. Both are members of Accademia delle Scienze di Torino.*

PERUCCA WAS SEATED at his desk thinking about this paper and waiting for his friend and co-author, when an old gentleman entered the room with an authoritative air.

"Professor, allow me to introduce myself: Polybius, the son of Lycortas, an historian of the second century, B. C."

"I am very honored, Mr. Polybius. To what do I owe the honor of your visit?"

"You are about to write an article on the pioneers of electrical communications. I should be very grateful to you if you would remember us, who believe we were truly pioneers of telegraphy. Think of the alphabetical code for visual signalling, described in my Ιστοριαϲ. You see, I am talking to you in the name of the syndicate of ancient communications, of which, by the trust the entire group placed in me, I am President."

"But," interrupted Perucca, "I see that you are well informed about our work; therefore, you probably know that we are going to write on pioneers of *electrical* communications."

This time it was Polybius who interrupted.

"Will you speak about kilometer, meter and centimeter waves, along with communication by radio?"

"We shall mention them, but only briefly," answered Perucca.

"Exactly," he continued, "and now that so much is known about the nature of light, won't you want to touch briefly upon radio communication using extremely short microwaves?"

Perucca was about to argue this point, when Polybius disappeared. Professor Gori had entered the study and Perucca had awakened with a start.

We are beginning badly, if we mix dreams with history!

## THE BEGINNING

The twenty-year period from 1729 to 1748 was characterized by an increasing number of experiments on the transmission of "electrical fire." It seems natural, therefore, that someone in that period would have thought of using the wondrous properties of this "fire" for electrical signalling at a distance. Such a thought is attributed to Benjamin Franklin and even though his attempt—a line four miles long (6.5 km)—failed, perhaps because of defective insulation or perhaps because the electrostatic condensers were too weak, this did not detract from the importance of the idea.

But electrical signalling without a code is not telegraphy; the use of an alphabetical code for transmission of a language had been proposed by Polybius in an era when long distance transmission was limited to the use of a few torches. Since at least one other alphabetical code is known to have existed prior to that of Polybius, one must bear in mind that the latter only modified it.

In the transmitting station, two groups of three and eight torches (or similar fires) formed two clusters of three and eight lights, respectively; when kindled fully or partially in all possible combinations, they provided twenty-four distinct signals, as many as there were letters of the alphabet (Julius, The African). Polybius proposed the use of two clusters of

five lights each, and from them he got twenty-five signals, using only ten lights.

The practical need to use a code for alphabetical transmission was not ignored by many pioneers in electrical communications. For example, the anonymous C. M., to whom the first project on electrical alphabetical communication is attributed (the pith-ball telegraph), used as many separately insulated wires as there are letters of the alphabet. This multiplicity of wires rendered practically useless not only this particular method of transmission, but all similar many-wired systems developed during the next three-quarters of a century, even after the advent of galvanic electricity in which the electric current is generated by Volta's pile.

In the 80 years following C. M.'s proposal, we acknowledge only two essential achievements in telegraphy.

In the first experiments already referred to, "electrical fire" seemed capable of an infinite velocity. The idea must have been unacceptable to many, and although it had been known for some time past (Ole Romer, 1675) that the velocity of light was very great, no one seems to have recognized the relationship between the velocity of light and that of electricity. This would have explained the "infinite" velocity experimentally found for the electrical fire.

The concept of infinite velocity was certainly not accepted by James Alexander, who in 1756 suggested to Franklin that the electrical experiments be repeated, using a thousand-mile line instead of the short lines which had been used previously.

Franklin's immediate reply, precisely two centuries ago, may be considered somewhat inexact and unacceptable today; however, in our opinion, it was a broad and penetrating idea, commonplace today, yet still far from being completely mastered by the physicists of the 18th century: to explain this spectacular velocity of electricity along the wire, he postulated that it was not the electric fluid itself which travelled the entire length of the wire at such a high velocity, but rather it was a question of the propagation of motion.

> If the [said] tube be filled with water, and I inject an additional inch of water at one end, I force out an equal quantity at the other, in the very same instant.
>
> And the water forced out at one end of the tube is not the very same water that was forced in at the other end at the same time; it was only in motion at the same time.

The water itself does not travel at a great speed, but the speed of displacement may be great.

Actual measurement of the speed of electricity along a conducting wire was not made until 1834, by Charles Wheatstone.

The other important development in the 18th century was the work of the Jesuit father Joseph Bozolus (1767), a professor of philosophy at the Roman Collegium, who experimented by transmitting an alphabet using only one electric line of two parallel insulated wires; the gap between the wires at one end of the line was used for connecting the plates of the Leyden jar; then a spark burst in the little gap at the other end.

The interesting feature of Bozolus' system was his alphabetical code, made by combining a certain number of successive sparks at irregular time intervals. Morse's code, some seventy years later, was of the same type, but considerably more practical.

One might mention the electrostatic telegraph of the French mechanic L. Lomond (1787). However, the account which we found of it was too abstract to permit a full understanding of its operation. In conclusion it is stated that Monsieur Lomond electrically transmitted messages to Madame Lomond across the house by means of only one conducting wire.

### ELECTRICAL COMMUNICATIONS BY WIRE

The new century began with the announcement of Volta's pile and the continuous electric current. In the same year the Spanish physician and physicist Francisco Salva y Campillo, who had previously invented a telegraph run by electricity produced by friction, used galvanic current (from Volta's pile) to transmit signals.

Following this discovery, experiments with telegraphy increased tremendously during the first years of the new century, and, at the first indication of the practicality of the telegraph, a number of patents were issued.

We should like to mention Samuel Morse immediately, but it seems better to talk of Volta first, for he also attempted to use electricity for transmitting at a distance. He introduced electrolytic methods of receiving signals, but the discovery of electromagnetism, tweny years later, by H. C. Oersted* (1820), gave rise to a new series of accomplishments.

These accomplishments are associated with names highly esteemed among physicists. Oersted himself began the series, and two other illustrious men we cannot forget here are Gauss and Wheatstone.

Carl Frederick Gauss, the giant of physics and mathematics, together with his colleague W. E. Weber, apparently had no intention of creating a telegraph—he wanted a rapid means of communication between the physics department and the observatory in Göttingen, a distance of 1.5 km (1833). He devised a practical communications system, using one line with two wires and a needle galvanometer to receive the messages. He used a code composed of groups of successive deviations of the needle, both positive and negative.

After a number of attempts, Charles Wheatstone, well-known inventor of the Wheatstone bridge, and William Fothergill Cooke perfected (1840) a telegraph with only one galvanometer needle and only one line, which was constructed and remained in use in England for several decades.**

*Perhaps also announced by the writer and journalist G. B. Romagnosi, a dilettante in "electricism." He probably described it, but in such an obscure and incomprehensible article of August 3, 1802, published at Trent in a periodical entitled **Ristretto del Foglietti Universali**, that it is quite difficult to understand which phenomenon he was referring to.

**The first telegraphic line, under the Wheatstone-Cooke patent, released on June 12, 1837, was put in service (1838) between London and West Drayton (13 miles) for the Great Western Railways Company. The original line had 5 needles and 5 wires; this was reduced to 2 needle and 2 wires, and finally to 1 needle and 1 wire (in the 1840 patent), because the Operators found this type quicker and easier to use.

Both Gauss and Wheatstone used positive and negative impulses always of the same length for their codes. In the code used by Gauss and Weber, as many as four such successive impulses were used to represent one letter. When the Morse code was established, only one type of impulse—either always positive or always negative—was used. However, the code with both signs of the current was later re-introduced and was widely used in such applications as W. Thomson's syphon recorder, for example.

In 1837, five years after the famous trip aboard the *Sully*, during which time he developed the idea of his telegraph, Samuel Finley Breese Morse finally obtained a patent for it. But seven more years passed before the first official telegram was transmitted (Washington to Baltimore, May 24, 1844) with his apparatus.

For a century the Morse telegraph has maintained its popularity in the face of more recently developed instruments, mainly because of the basic nature of its operation and the simplicity and strength of its component parts. For example, in Italy there are still 15,000 registered Morse telegraphs, as compared to 3000 teletype systems.

The history of those years from 1832 to 1844 reveals a sordid story of dishonest business interests which developed over patent rights; but it also records innumerable episodes worthy of the purest sentimentalism.

Just to pay homage to Morse, we will mention the malevolent comments on his work which appeared in a recent Italian book on the history of science; but, in the same book, the malignant criticism is largely neutralized by these lines: "from this type of telegraph of (1837) to that of the present day, which still bears Morse's name . . . the most important innovations were introduced by Morse himself."

We should also like to mention sweet Miss Annie Ellsworth. During the blackest, lean years for Morse, on the evening of March 3, 1843, he was waiting for the law on telegraph appropriation, already approved by Congress, to be signed by President Tyler. On that evening, Congress was closing its session and preceding laws also needed the President's signature. Morse, who was waiting in the Congressional room, finally gave up hope and went home to sleep. The next morning Miss Ellsworth, the daughter of the Commissioner of Patents, brought him the happy news that the bill had been signed.

What did Morse offer her in his gratitude? She was to transmit the first message. And thus it was: Miss Ellsworth on May 24, 1844, selected the message "What hath God wrought." Morse himself, with this verse of the Bible, sent the first official telegraphic message in the United States, seated at his apparatus, installed for the occasion in the Supreme Court room of the Capitol. Alfred Vail, Morse's able collaborator, received it at a distance of 70 km in the Mount Claire railroad station in Baltimore.

Would it have been better to have rewarded Miss Ellsworth with the promise of future shares of stock in the Morse Telegraph Company? We Latins do not think so, and in Morse's action we find a sentiment which renders him a dear fellow to us.

With this apparatus and the Morse code, the telegraph was born, and by the middle of the century it has been established internationally.

Actually the name "telegraph" had been coined by Claude Chappe (1791) to identify his device for optical transmission and the term became popular, particularly in France and Russia. All children that still read Alexander Dumas' stories know that the Count of Montecristo often used the optical telegraph.

There was, however, a great need for a receiver capable of tracing the signs of the code; only in this case could the apparatus deserve the title of telegraph. It is difficult to say who was the first to realize the advantage of a means of recording the incoming signals. Perhaps it was Harrison Gray Dyar (1828), or Edmund Davy (1838), or Alexander Bain (1846), or even Morse himself (1832).

In the equipment used by Morse in 1844, the signals of the Morse code were received on a strip of paper tape in the form of permanent mechanical impressions. It was then a true telegram. An almost incredible number of different systems were suggested before a definitive one prevailed in practice—the one which records in ink.

Augustus Steinheil, however, was the first to use a device giving a permanent record—in the form of dots on a paper ribbon. His practical telegraph, based on the system developed by Gauss and Weber, was already functioning in 1837 between München and Bogenhausen (3 km).

### INCREASE IN NUMBER OF SIGNALS

The Morse code used about forty different signals, enough to transmit letters, numbers and punctuation. The next step was to use the normal alphabet—the dream of the anonymous C. M. Wheatstone also had thought of receiving the signals on an alphabetical dial (dial telegraph). At about this same time the printing telegraph was developed. Alfred Vail, Morse's collaborator, mentioned in a book (1845) that the printing telegraph was in existence in 1837.

The alphabetical telegraph, whether or not it printed, necessarily introduced synchronism into electrical communications. There were two types, both of which were outstanding. One was the start-stop type, exemplified, for instance, by Wheatstone's printing telegraph (1840). This type is often attributed erroneously to Ludwig d'Arlincourt (1861). The other was a true synchronism, of which there was a classic example in David E. Hughes' printing telegraph developed in 1855, but applied to international use only since 1868.

The start-stop type was so devised that through the same electric impulse, one sending and one receiving device were disengaged simultaneously (with the exception of the time necessary for the electric transmission). Both devices completed one cycle (usually one revolution of the wheel) within the same time. If there were, for example, 40 signals to be distinguished, the same number of electrical contacts uni-

formly distributed along the edge of the two wheels could effect a two-way correct correspondence between the transmitted signal and the received one, if synchronism between the two wheels were accurate to about 1 per cent. Synchronism within this limit was delicate but not difficult.

If one considers that in the present teletypewriters there are only five signals, to which are added the disengaging signal and a final signal to reset the machine, the start-stop seems an apt device for a rudimentary but adequate synchronism.

True synchronism may be obtained, and we might even add "easily," as long as the transmitting and receiving instruments are tightly coupled. Paul La Court's phonic wheel (1878) served excellently for a number of decades, and we would not say that the assemblies used today in television are conceptually different, although a great deal more refined.

The start-stop principle and the principle of true synchronism have alternated in popularity in telegraphy. At present, with the preeminence of the Baudot code, the start-stop principle predominates. In the transmission of images, however, particularly in television, true synchronism is used.

P. L. Schilling may be called a pioneer in the Baudot code. In the same year (1833) in which the Gauss and Weber telegraph appeared, Schilling pointed out that by combining two opposite signals, furnished by a direct current either positive or negative, there resulted from five successive impulses a number of distinct signals ($2^5=32$) sufficient for telegraphy. But Schilling made the mistake of using five lines for transmission and five needle galvanometers for reception; in this way the five impulses which determined a letter could certainly be simultaneous, instead of being in a series as in Baudot's code; but the advantage derived from the speed of transmission could not compensate for the expense of the multiple line.

Emile Baudot amended this code (1874) by using a series of impulses on one line only, and so the code must be associated with his name. The intrinsic value of the code was the uniform balance in the composition of each signal: five impulses (positive or negative) were necessary and sufficient for each one.

Baudot merits a place of the highest honor in the history of the teletypewriter, by virtue of his *combinateur* or printing translator. It is the device for automatically translating each electric signal of Baudot's code into a printed letter.

Baudot, an engineer in the Post Office and Telegraph Company of France, did not perfect his translator without a great deal of work: the device which evoked a favorable comment from his superiors was the thirty-third! But, when he made his first test between Paris and Bordeaux on November 12, 1877, the apparatus at once proved to be a huge success.

The translator did not solve the entire problem of the teletypewriter, but it was an essential part of it. The teletypewriter uses a standard typewriter keyboard, so arranged that when a key is struck, the five impulses of the corresponding letter, plus the two terminal signals, are sent. At the receiving station it is necessary that the set of arriving impulses activate the translator in order that the transmitted letter can be imprinted upon paper. Every teletype station must have a translator fit for both sending and receiving letters; H. L. Krum and E. Kleinschmidt introduced it during the years of the First World War. Thus, the teletypwriter was born, and as far as it is economically feasible, it has replaced every other type of telegraphic machine.

The next—more ambitious—aim was to transmit telegraphically a manuscript or drawing, or even a picture, perhaps even a picture in color. For this process, it was necessary to increase greatly the number of distinguishable signals. The original 32 signals in the Baudot code were expanded to about 60 through using double rows of symbols similar to capital and small letters on a typewriter. Even this was by far insufficient to transmit pictures, and a new system had to be developed for sending halftone reproductions and for use in television.

In halftone photo-engravings, the image is formed of a lot of black dots—from 1000 to 5000 per square centimeter according to the degree of refinement required in the reproduction. For satisfactory but less detailed reproductions, such as appear in newspapers, a smaller number of dots per square centimeter is sufficient. In order to transmit a picture electrically, with the same degree of refinement that a photo-engraving has, one needs as many distinguishable signals as there are dots. If a color reproduction is desired, a trichromatic method is used, tripling the number of signals.

Although telegraphic transmission of images does not require perfection attained in certain methods of photo-engraving, thousands of distinct signals are still needed to define the reproduced image.

For certain types of handwriting transmission (facsimile), a simple apparatus such as Elisha Gray's teleautograph (1893) was—and is—quite sufficient.

But, preceded by initial developments by Bain (1843), Blackwell (1847) and Hipp (1851), Giovanni Caselli's pantelegraph must be mentioned. It was put in service in 1855–56 and tested on the Paris-Amiens line until 1861. It was then placed at the public's disposal, on the Paris-Lyon telegraph line on December 16, 1865, and later, on the Lyon-Marseilles and Paris-LeHavre lines. However, a full quarter of an hour was needed to transmit one image. The transmission proved to be so expensive that the pantelegraph lines were taken out of service after three years.

Nevertheless, two very fundamental concepts were established with this instrument, which can be considered the prototype of modern phototelegraphic and television equipment. In the pantelegraph, correct scanning of the image and adjustable synchronism at the receiving station were attained. Today, although about seven minutes are still needed to transmit a 10 cm $\times$ 12 cm image by phototelegraphy, a television image is registered in about 1/25 of a sec-

ond. With television, moreover, there is simultaneous sound transmission.

Everyone knows that nowadays living scenes and movies are the daily program of Television. This is the culmination of the efforts of G. R. Carey (1875), who was the first to use selenium in photoconduction, and of Paul Nipkow (1884), who invented the first scanning device—Nipkow's disk.

Finally, telephony was an even more ambitious goal for electrical communications. A famous popular science writer, Guillaume Louis Figuier, in the middle of the 19th century wrote: "Telephony or musical telegraphy has as its purpose the establishment of correspondence between two distant persons by means of a combination of a few easily recognized sounds." Well, it is a rather uncommon definition, but we can accept it!

It is a pity that there is so much bitterness associated with the invention of the telephone, an invention we do not hesitate to consider the greatest aid to human affairs which man has ever invented.

The reader of these pages will realize that the pioneers in electrical communications often had trying years, and not only due to difficulties encountered in their work—for this would only add to their fame —but there were difficulties caused by business disputes, and from these no one, pioneer or not, emerges greater or purer.

The history of the telephone, like the histories of other significant inventions, reveals a rather sordid story in which the justifiable ambition of the inventor meets with the meanest business deals and national prides.

Innocenzio Manzetti, an obscure mechanic from Aosta, Italy, probably had the original idea for the telephone, or perhaps it was Antonio Meucci, a Florentine artisan who migrated to Havana and then to the United States, or Phillip Reiss, or perhaps still others. Certainly it was Reiss (1860) who first used the name "telephone" to designate the entire apparatus.

The question of who invented a reasonable transmitter is also a very difficult one. Charles Bourseul, an official in the French Post Office and Telegraph Company, proposed (1854) to modulate a current by using a thin plate which, vibrating as a result of sound waves, would open and close the circuit. Phillip Reiss built such a device in 1860. Of course, it did not have the fidelity to reproduce recognizable words; it could repeat a sound so far as it contained one dominant frequency.

In the beginning, in order to have telephonic current modulated by a voice, Manzetti, Meucci (1871),* Bell (February 14, 1876) and others who, almost simultaneously with Bell, filed their patent applications for a telephone (Elisha Gray, February 14, 1876, two hours later than Bell; J. W. McDonough, April 10, 1876), all used the reversible telephone. But the energy obtainable in the modulated current was so weak as to be serviceable in a line only several hundred meters long. Still more, this possibility could only exist owing to the extreme sensitivity of the human ear.

Then to whom are we indebted for the telephone? We would say:

(1) To Hughes (1877) belongs the credit for the carbon microphone and for this name. This can supply an audio current with a power greater than that which a simple telephone can produce. The names of the following should be associated with Hughes: Thomas Alva Edison, Emile Berliner and, especially, Henry Hunning, who had first proposed a granular carbon microphone.

(2) To Edison (1877) goes the credit for the microphone transformer which, by increasing the voltage of the audio current, permits a long distance transmission.

(3) To Alexander Graham Bell goes the honor of founding one of the most grandiose of technical-industrial, and later scientific, organizations in existence.

On October 9, 1876, the first telephone line in the world was put into service, connecting Boston with Cambridge, Massachusetts, a distance of a little over three kilometers. In March of 1877, subscribers were accepted. The first telephone exchange in the world was established several months later at Lowell, 40 km from Boston, with 45 subscribers. On July 9, 1877, the Bell Telephone Company was founded and by the end of that year there were 2600 telephones in use in the United States.

In January, 1878, telephone offices were opened in New Haven and Detroit. By 1900, two million telephones were in use throughout the world. In 1952, approximately eighty million were in existence, of which forty-nine million were in the United States. Washington has more than one telephone for every two inhabitants; in Milan, there is a telephone for every three inhabitants.

A new chapter in the history of the telephone began with the Connolly brothers and MacTighe of Washington (1879). They developed an automatic telephone exchange with eight numbers, and demonstrated it at the Paris Exposition in 1881. In 1886, G. B. Marzi independently designed and constructed the first automatic telephone exchange with ten numbers, which operated for three years in the Vatican Library.

But the automatic telephone really became a practicality with Almond B. Strowger's patent application (1889) for a telephone exchange of a thousand numbers. The patent was granted in 1891, and in 1892 the first automatic telephone exchange was opened to the public, in La Porte, Indiana.

Progress was slow. Even in the 1902 edition of the *Encyclopaedia Britannica*, a telephone exchange with two thousand numbers was cited as the largest, but there were also prudent comments on the possibility of fuller developments. Europe had to wait until 1908 for the opening of its first automatic telephone exchange (Hildesheim, 1200 numbers).

*Only in 1886, three years before his death, did he see the priority of his patent recognized by the Supreme Court of the United States, but it had expired years before that.

LINES

So far we have discussed only telegraphic devices, but the importance of the line was immediately evident in order that the cost of each type of telegraph might not become prohibitive. Therefore, in the preceding pages we have mentioned only very briefly the telegraphic methods which used more than one line. Furthermore, was a line to contain two wires, or, more economically, one wire, since it uses ground to close the circuit?

There is quite enough material on the use of only one wire to write a lengthy history of lawsuits and first rights of invention.

Steinheil (1838) found out that he could transmit even if one wire of the two-wire line was broken and on the ground—but others had already pointed that out. Then there was Francisco Salva who, anticipating what might be easily deduced quantitatively by applying Ohm's laws (1827) to an earth plate, pointed out at the end of the 1700's that a galvanic current could use the ground as a return lead—a fact which had been known about electric fire for a century.

Was the use of only one conductor for the transmission of electrical communications a true improvement? Even now it is difficult to answer affirmatively. If there are many telegraph lines in a region with a single conducting wire (the return lead being the ground) some inconvenience can arise and the more costly and more advantageous two-wire lines are preferable.

Once the telegraph had been proved practical, the next goal was to join the most distant parts of the world. But the energy conveyed along the line was quickly exhausted, and in the useable conducting wires (iron, brass, copper) a relay was needed about every ten kilometers to recharge the line without distortion of the signal.

Morse, together with Leonard D. Gale and Joseph Henry, made an elementary relay, but a more complicated problem arose as soon as it became known that a signal was distorted on a long aerial line, and to an even greater extent in an underwater cable and in a grounded one.

The idea of spanning the Atlantic Ocean with a telegraph cable had already been Morse's dream (1842), but what a long story was involved in its realization! Made possible by the use of gutta percha insulation (W. Siemens, 1846), this project was to see its practical fulfillment after two big failures, only at the laying of a third transatlantic cable in 1866.

The following contributed substantially to the success of the transatlantic telegraph cable: William Thomson's use of the syphon recorder (1867); the Morse code in the form known as trivalent, also attributed to Thomson (instead of sending unidirectional dots and dashes, both negative and positive impulses are used, one for the Morse code's dots and the other for the dashes).

The difficulties encountered in underwater telegraphy gave rise to many important theoretical studies, such as Thomson's works, and, much later, those of O. Heaviside (1889). From the works of the latter, the terms *pupinization* (Michel Pupin, 1899) and *Krarup* loading (Karl Emile Krarup, 1902) of the cables claimed their origin. As a result of these studies, the speed of signal transmission was increased and signal distortion was reduced, both within commercially acceptable limits.

Neither of these two methods for improving the properties of lines has lost its importance, even though the advent of electronic amplification has provided considerably more efficient methods for multiplying the effective transmitting distance and for overcoming signal distortion. Electronic amplification appears even more powerful when one considers the part it plays in long distance telephony, at distances previously considered impossible.

It behooves us, nevertheless, to mention that, before the advent of electronics, the telephone relay (for example, H. E. Shreeve's mechanical amplifier, 1903) had also achieved some promising results in long distance telephony.

The problem of the highest utilization of the line became more urgent as the length of the line increased. Now, for several years past, this subject has been included as a regular chapter in texts on information theory, but, in an empirical form, it had become apparent soon after Morse's initial experiments.

To Bain (1846) goes the credit for the perforated paper strip, prepared at the telegraphic sending station according to a code patterned after the Morse code, and then placed in the transmitting apparatus. Wheatstone's automatic telegraph (1859) is the very machine which, by substituting the perforated paper strip for manual operation, increases appreciably the speed of telegraphic transmission and the utilization of the line. Today it is said that it "increases the flow of signals" on the line.

A simple instrument (the duplex, 1853) was suggested by Julius Wilhelm Ginth to effect simultaneous telegraphy in two directions on the same wire. The same concept was later perfected by use of the artificial line (1854, C. Frischen; 1872, Joseph Barker Stearns).

Only two years after the duplex system, the diplex was suggested (1855) by Stark, whereby two telegrams could be sent in the same direction on the same wire at the same time. Other complex transmission systems followed, such as Edison's quadruplex (1874) and the various multiplexes.

Moses G. Farmer introduced the idea of sharing one telegraph line among several pairs of users, by placing it successively at the disposal of each pair for a very brief time, but sufficient for the transmission of each one's message. To Baudot, however, goes the credit for the first multiplex system (1874).

In connection with the problem of the highest utilization of the line, three other developments are worth mentioning:

Francis von Rysselberghe solved (1887) the inviting problem of telegraphing and telephoning on the same line.

Edmond Laborde pointed out (1860) that the possibility of simultaneously sending alternating currents of different frequencies on the same line and picking them up at the other end of the line with separate resonant receivers (the principle in substance was that of the vibration frequency meter).

Paul La Court (1873) used this principle for a multiplex transmission, but Elisha Gray's name is especially remembered among the pioneers (1874) of this harmonic telegraphy, which could transmit up to a dozen messages on one line at the same time.

Whom must we remember at this point as the pioneer in the use of electromagnetic waves on a wire, modulated to transmit signals, either telegraphic or telephonic, or both, or even better, a wire carrying at the same time a lot of channels on each of which a communication distinguishable to a distinct receiver could be sent? To this unknown pioneer must be given the credit for the prodigious results of the hundreds of channels used today in a single coaxial cable.

### PARENTHESIS

Here we must pause for two reasons:

One, the techniques which science in continuous development has placed at our disposal, are gradually bringing together, in the field of electrical communications, the use of both types of communication —with and without conducting wires.

Two, we want to limit ourselves to the pioneer phase only, but we can no longer overlook relatively recent contributions, especially in the field of electronics. Without this mention of electronics, we have experienced some difficulty in writing our preceding pages.

It is very doubtful that J. J. Thomson, W. Kaufmann and F. Braun could have foreseen the ultimate uses of cathodic rays constituting, according to O. Lodge's picturesque expression, "the fourth state of matter." It is equally doubtful that T. A. Edison, H. Hertz, G. Elster, H. Geitel, or even O. W. Richardson could have foreseen the uses of thermoelectrons and photoelectrons.

We would say that the first practical applications of electronics were J. A. Fleming's high frequency rectifier diode and the triode announced almost at the same time by Robert von Lieben (Austria, March 4, 1906) and Lee de Forest (U.S.A., October 25, 1906).

But prior to these, Ferdinand Braun comes to mind. At least two devices which are among the most significant in current electrical communications technique claim their origin in this man's studies: the crystal rectifier (1877) and Braun's tube (1897) which, after having been used in the first quantitative experiments on the nature of electrons, has become the progenitor of the cathode ray oscilloscope which can be considered unquestionably the very heart of the countless wonders of modern techniques—from radar and related instruments, to television, to devices which can measure time in millimicroseconds.

Here we meet Lee de Forest, who, protected by all-inclusive patents, was strongly determined to extend his authority upon a lot of inventions, and to go down in history as a leading figure in litigation.

But in texts which seem to be devoid of prejudice or concealed profits (and in the first decades of the century there was a great deal of these), von Lieben is given as the inventor of the telephone thermionic amplifier (1911), and to Alexander Meissner (1913) is attributed the oscillator employing an electrical triode.

Now none of the three would have made much progress without the work of Irving Langmuir (1913) and the contemporary work of H. D. Arnold, who showed the necessity of using very high vacuum tubes to attain the required constancy and fidelity.

And now let us remember at least two more names: the thermoelectronic oscillator would not have reached its present stage of development without W. G. Cady's researches (1922) on the use of quartz (piezoelectric) plates as the best frequency controllers and without G. W. Pierce's (1923) oscillator circuit, stabilized by means of a piezoelectric plate.

### WIRELESS

One of us, fearing another visit from Polybius, would have maintained that visual signalling between stations in ancient times was really electromagnetic communication. However, the ancients were content to keep the same system for thousands of years, without making perceptible improvements.

It is necessary to come to Claude Chappe (1791) in order to find a substantially improved optical signalling system, and we have already said how wrong it was to invent the name "telegraph" just in order to baptize it. The system was a network of stations for regular service between distant cities. Between Paris and Lille, for example, a distance of about 200 kilometers, 22 repeater stations were needed. At the time of Napoleon's downfall, the network in France consisted of 1800 km of "telegraph lines" and the number of stations rose to 533 before the advent of electric telegraph. The system was also used in other countries, notably in Russia.

But Chappe's work was a swan song rather than that of a pioneer, and optical transmission has no place here.

"Wireless communication" has a very different meaning.

History tells us how the philosopher Giambattista Della Porta, known to many for his *Magia Naturalis* (1569), described therein an experiment with magnetic needles, in which, as one needle was turned on an alphabetical dial, the other turned just as much on a similar one, so that both were indicating the same letter. And the story had some credit, even though it was prudently stated that not every magnet can produce such "sympathetic" needles. It seems that Galileo himself considered the possibilities of transmitting signals at a distance "by attraction of needles." A serious word came from a French father Leurechon, who maliciously wrote about such a discovery: "It is wonderful, but I do not believe there is such a magnet; moreover, it is not practical [imagine!] since be-

travals would take place too frequently and too mysteriously."

Yet in 1711, in Addison's *Spectator,* the story was repeated, embellished with the moving episode of two friends who communicated with each other across cities, mountains, seas, deserts, and even an entire continent. It later became poetry.

Again: "wireless communication" has another quite precise meaning; there was no hope for a reasonable method of wireless electrical communication until the discovery of magnetic induction (1831, Michael Faraday); but the hope, which was born in Morse himself, was short-lived. Not until J. C. Maxwell's powerful synthesis and H. Hertz' miraculous experiments was it possible to transmit energy by electromagnetic waves and to produce and receive such waves. Well, it seems that neither of these great physicists was concerned with using his waves for the transmission of signals.

It was up to a self-taught, persevering young man from Bologna, endowed with a rare understanding of physics, the twenty-year-old William Marconi, to begin (1894) the research which led him to results worthy of the fame and honor bestowed upon him.

In the beginning things were difficult for him also, even though his difficulties did not last as long as Morse's for example. Marconi also suffered from the skepticism of responsible agencies, the irony of several contemporaries, the disputes over priority and the struggles to establish his transmission system on a practical basis.

Marconi certainly made use of devices which were already known (Augustus Righi's oscillator, O. Lodge's coherer, Popoff's antenna). It must be said, however, that he substantially improved each one.

In our opinion, in the very beginnings of radiotelegraphy when very little was known about the importance of the ground and of the antenna's functions, the greatest credit due to young Marconi is for having realized the overwhelming importance of tuning between transmitting and receiving stations. Marconi probably would have had very poor results from his tests if he had not held steadfastly to this belief and cherished it, as far as possible, from the very beginnings of his experiments, when he succeeded in transmitting wireless signals up to a distance of several hundred meters (1895, Pontevecchio, near Bologna).

Two years later (1897) wireless telegraphy was established across the Bristol Canal (5 km between Lavernock Point and Flatholm). Two years later the English Channel was spanned (50 km) and two years after that, the Atlantic Ocean between Poldhu (England) and S. Giovanni di Terranova—a distance of 4500 km, on December 12, 1901—too.

Distance had been conquered quickly by wireless telegraphy, but by very primitive means. A long road still lay ahead, but it was travelled in a few decades!

Electromagnetic waves from a spark generator were notably weak, and no means was known at the end of the century for obtaining the continuous electromagnetic waves needed for radio telephoning. With W. du Bois Duddel (1900), who recognized the negative resistance characteristic of the arc and hence the possibility of obtaining from it a persistent oscillation with fixed frequency, hopes of generating continuous oscillations of high frequency (on the order of $10^5$ cps) took shape, and a little later (1903) they were realized by Valdemar Poulsen.

This did not stop F. W. Alexanderson, spurred on by R. A. Fessenden, from constructing a high frequency alternator (still only $0.5 \times 10^5$ cps) with an iron rotor (1906). It did not prevent R. Goldschmidt (1907) from making his medium frequency alternator to be used in connection with a frequency multiplier. Thus in a very well known treatise, much later (1926), the generators of high power continuous waves are mentioned in order of importance—and the order is exactly Poulsen, Alexanderson, Goldschmidt. Oscillatory circuits using thermoelectronic tubes are still neglected.

With the realization of continuous waves, Fessenden's ardently desired dream of radiotelephony by means of modulation of carrier waves finally came true. Radiotelegraphic communication was established on December 11, 1906, between Brant Rock and Plymouth, Massachusetts (18 km). A few days later Telefunken sets were attaining 40 km (December 20, 1906).

Two years before this (*Rend. Acc. Lincei,* Vol. 13, p. 86, 1904), Quirino Maiorana's account of his experiments with the wireless telephone appeared. He communicated telephonically between two distant points of the Istituto Superiore delle Poste e Telegrafi (Rome) through numerous intervening walls of the building. A little while later he repeated his experiments between the same institute and Monte Mario (Rome), a distance of 4 km.

After an interval of fifty years, it is easy to judge how "out of line" Maiorana's complex apparatus was. After improving his equipment, and by using Poulsen's arc (instead of the previous high frequency spark), he achieved radiotelephonic communication (1907) between Rome and Messina, a distance of 500 km; but at the same time Fessenden had just spanned the 500 miles separating Brant Rock from Washington.

These are the same years which mark the birth of the thermionic tube, but a number of years went by between its first applications in radio receiving and the time when its paramount importance was asserted in the generation and amplification of high frequency oscillations. One must bear in mind that in 1914, yet, Marconi described and patented a multiple spark transmitter to obtain "nearly" continuous oscillations.

A little later (1915), a small electronic generator, producing a very weak antenna current, was experimented upon in Italy.

### RADIO TRANSMISSION

For many years several fundamentals of radio transmission were unknown. Gradually the use of long waves in long distance transmission gave way to short waves. Marconi's name is still (1916) associ-

ated with research on short waves and their practical acceptance. We should mention as pioneers the large number of amateur radio operators during the 1920's.

To short waves ($\lambda = 20 \div 100$m) falls the honor of having for the first time circled the world, a trip requiring a little less than ⅛ second. It was only in 1924 that the first radio communication between aircraft and ground stations was finally established by short waves, and this contact, made so tardily one might say, was spectacularly successful: from a ½-watt transmitter in the aircraft, communication was established with ground stations at a distance of approximately 3000 km.

Later on, research entered the field of ultra-high frequency waves ($\lambda = 2 \div 10$m).

Before the introduction of these ultra short waves, there was some attempt to find the direction of the received wave. The radiogoniometer of E. Bellini and A. Tosi (1907) is the only apparatus to be remembered here.

Afterwards, through use of the ultra-high frequency waves, wireless came to the straight line radio communication, which owes its development to ever-shorter wavelengths, down to decimeter values. Here the parabolic reflector gives a gain of $10^3$ both in transmission and reception; here the power of a 1-watt transmitting set is as effective in the favorable direction as a 1-kw transmitter.*

### ELECTRICAL COMMUNICATIONS IN A BROADER SENSE

In the preceding pages we have limited ourselves to the more outstanding phases of electrical communications in a strict sense: the exchange of signals from a transmitting station to a receiving station, both of which are prepared for the exchange. Several cases of electrical communications in a broader sense, then, have not been mentioned as yet. We turn to these briefly.

Alexander Popoff was the first to pick up electromagnetic waves from a distant thunderstorm. During recent years Harald Norinder, in Uppsala, has been methodically studying the electromagnetic waves generated by these discharges and from them he plots storm charts—a field of research which is very promising in atmospheric physics.

We believe everyone has heard of the wonders of radar and analogous systems during the war, and even more in peace. We deeply regret that we don't know the names of the pioneers to whom we owe such a useful invention.

Nor should a word pointing out researches and results in regard to telluric currents be considered foreign to our theme in general.

Finally, referring to radio astronomy which has become so popular recently, we believe that the scientists engaged in this field are all pioneers in "active service"—it will be necessary to wait a few years before discussing this item.

We have the impression that he who shall look at the pioneers in communication in a few decades, will find the time to be already ripe to say a few words on pioneers in the science of information theory. We have not discussed it. We have remained silent about too many things within these few pages.

### CONCLUSION

We have finished. But while putting down the pen and taking a glance at the past two centuries which we have tried to evoke here, the words of Benjamin Franklin come to mind:

There are everywhere a number of people, who, being totally destitute of any inventive faculty themselves, do not readily conceive that others may possess it; they think of inventions as of miracles; there might be such formerly, but they are ceased. With these, every one who offers a new invention is deemed a pretender; he had it from some other country, or from some book; a man of their own acquaintance, one who has no more sense than themselves, could not possibly, in their opinion, have been the inventor of any thing. They are confirmed, too, in these sentiments, by frequent instances of pretensions to invention, which vanity is daily producing. That vanity, too, though an incitement to invention, is, at the same time, the pest of inventors. Jealousy and envy deny the merit or the novelty of your invention; but vanity, when the novelty and merit are established, claims it for its own.

The smaller your invention is, the more mortification you receive in having the credit of it disputed with you by a rival, whom the jealousy and envy of others are ready to support against you, at least so far as to make the point doubtful. It is not in itself of importance enough for a dispute; no one would think your proofs and reasons worth their attention; and yet, if you do not dispute the point, and demonstrate your right, you not only lose the credit of being in that instance ingenious, but you suffer the disgrace of not being ingenuous; not only of being a plagiary, but of being plagiary for trifles. Had the invention been greater, it would have disgraced you less; for men have not so contemptible an idea of him that robs for gold on the highway, as of him that can pick pockets for half-pence and farthings. Thus, through envy, jealousy, and the vanity of competitors for fame, the origin of many of the most extraordinary inventions, though produced within but a few centuries past, is involved in doubt and uncertainty. We scarce know to whom we are indebted for the compass, and for spectacles, nor have even paper and printing, that record every thing else, been able to preserve with certainty the name and reputation of their inventors. One would not, therefore, of all faculties or quantities of the mind, wish, for a friend or a child, that he should have that of invention. For his attempts to benefit mankind in that way, however well imagined, if they do not succeed, expose him though very unjustly, to general ridicule and contempt; and, if they do succeed, to envy, robbery, and abuse.

Perhaps Franklin, while writing these golden words, thought of the skepticism with which his theory on the electrical nature of lightning was received. We are also thinking of the sneering words to which the painter Morse must have listened as he waited, without hope, as Congress discussed whether the American Government should stand the expense for a test of his telegraph. We are also thinking of that insignificant Italian magazine which repeatedly jeered at Marconi, inviting him to send a wireless message at least across the straits of Messina (4 km), if he could.

*Perhaps Perucca was dreaming again, when at this point the Greek historian reappeared.

"You were about to quote me again, but I thought it over. Down there," he said, "they have found out about my visit to you, and I was reproved because of it. I have resigned as President of the syndicate. I deserve it, however; I realize that there is nothing which relates my torches to radio communication."

"We agree, Mr. Polybius. I should like to beg you to pay, on our behalf, our homages to Ben Franklin."

As Polybius was just leaving, he turned with a contrite air:

"I cannot; he is in another section, on another level. He is among the benefactors of humanity."

At the beginning of this century, an Italian comedy became famous; its title was *Miseria e Nobiltà*. Why do these two words come to our mind at this time?

*Nobiltà*. One cannot think, without emotion, of the significance to humanity of the development of a method of wireless communication capable of travelling 300,000 km a second. Or, think of the importance of that "SOS" which comforts, helps and often saves people in danger at sea, in deserts, on polar icefields, or abandoned to their fate, in a lonely, inadequate hospital. We are reopening a volume in which a few of the above topics are treated, and in it we find an account of the Service for Radio Medical Assistance of the International Radio Medical Center for those travelling at sea. It is a service entrusted to Italy. We are proud of it, first as men, then (please forgive us) as Italians.

*Miseria*. It is the moral poverty frequently accompanying material wealth, which fed the most vicious business struggles, that developed over patents for electrical communications. Even in the selection of the distress signal "SOS," arrogance and prestige occasioned violent disagreements!

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# *LEAD TIME*

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Historians generally agree that in the annals of naval warfare, World War II was characterized by extraordinary technological development in the weapons of sea power. The refinement of sea-air operations, improvements in radar, sonar, proximity fuses, and finally the harnessing of nuclear power, were but a few of the sensational applications of scientific progress to the techniques and tactics of war at sea.

Much less dramatic, yet no less important, was the impact of these developments on our logistic capabilities. From a range of some 200,000 items required to support naval forces in 1940, we were handling close to 5,000,000 by the war's end.[1] Thus to the supply operator, the prime objective was to harness this swiftly growing demand and establish proper control over a vastly expanded range of material requirements.

How the Navy met this logistic challenge during the war and ultimately refined its management techniques in the creation of a modern supply system is well known. The pattern of control is now established, and by intensive efforts in item identification and cataloguing we have pulled that five million item figure down to around a million and a half without narrowing the range of items available to support the highly diversified needs of the fleets.

Today the Navy is on the threshold of progress which, in Admiral Carney's words, will make World War II "technically ancient history compared to the age of guided missiles, nuclear power, atoms and hydrogen." Certainly the potentialities of rockets, lightning communication, automation, and space travel tax even the wildest imagination in what the future may hold in further technical progress. But one thing seems certain: the keynote is *speed*.

Thus *time* is becoming a premium factor in virtually everything we do. Just as the past fifteen years have presented problems of logistic control, the future promises new challenges in speed, and "lead time" is likely to become a more vital consideration as we seek to accelerate the pace of logistics to keep up with the demands of the future. It seems appropriate, therefore, to re-examine the lead time factor and see if it poses any particular problems in meeting the demand for greater speed in modern warfare. The following comments are purposely broad, designed not to treat exhaustively with any of the propositions they pose, but rather to give a panoramic sweep over a wide range of possibilities in improving lead time.

Although elementary in concept, "lead time" is one of the most deceptive factors in the whole field of logistics. There are two reasons for this. First, the utter simplicity by which it is measured makes one vulnerable to the delusion that it can be shortened merely by reducing the number of days in an allowed lead time schedule and thereby automatically improve our logistic response.

Second, it is little recognized that "lead time" really encompasses more than is implied by such qualifying terms as "production," "procurement," "supply" and "logistics." Indeed, it embraces *all* the time between recognition of a need and the moment all requirements to accomplish a mission are met.

[1] VADM F. J. Horne, *Shipmate*, December 1944.

Certainly no one would argue that "lead time" is the *sine qua non* of the complex problems of logistics. But since time is becoming an ever more critical factor in defense, perhaps the following six considerations offer a basis upon which this factor can be used to greater advantage, and the problems of "lead time" minimized.

*Planned Requirements:* Built into the system for logistic support of the fleets and overseas bases is a procedure for the orderly build-up of material to meet either a new requirement or impending increases in existing demand. We call these "planned requirements," and they are added to the lists of existing needs either as additional quantities of current, run-of-the-mill supplies, or as new items not previously supplied.

It is vital to the activation of this process that a need be announced. In its purest sense, the awareness of certain needs to reach an operational objective may not always come in the form of a specific demand; it has only to be a manifest need for something, whatever it may be, to accomplish a task. This recognition must then be communicated to someone whose job it is to do something about it, whether it be a scientist to develop a new device, a manpower boss to recruit and train men, or a supply operator to get materials. The point is that when this need is communicated, the logistic process begins, and it is this *announcement* that triggers the entire logistic apparatus.

It often happens in practice, however, that plans are completed for the deployment of a unit, or the construction of an installation, or the introduction of new models of existing equipments into an operating area, without timely notice to those whose responsibility it will be to support such elements. When this occurs, operating requirements often appear in the form of emergency demands involving wholly unacceptable lead time factors.

In the Far East during Korean operations, for example, a major communications installation was contemplated which would involve (1) some of the latest in radar and radio equipment, and (2) considerably increased demand for common electronic parts already on hand in the area in minor quantities. It was only as specific demands were generated from actual operation of the completed installation, however, that the logistic processes were activated. Initially, most of the demands had to be processed as emergencies, and the lead time involved was often a critical factor. An orderly build-up commencing with the moment it was decided to install the facility, however, might have prevented at least some of the urgencies which developed later.

Thus it seems clear that *the moment a demand is manifest, lead time begins,* and how one uses the time following such discovery is crucial. The determination of need is basic, and "lead time" lies in the interval between the "what" and the "when." The longer the interval of time, the better is one's planning. The shorter the time, the more acute is the emergency.

The crucial period between recognition and announcement, however, is not a mathematical constant in its effect upon the total "lead time." Thus, for example, ten minutes delay in calling a taxi to catch a train may not mean simply that one will be ten minutes late at his ultimate destination. If, as a result of the ten minutes delay, the train is missed, he may not arrive for twenty-four hours later than planned. The total loss of time, therefore, is considerably more than the few minutes delayed initially, and in logistics the operation of this simple principle can result in weeks or months of lost time.

In coping with precisely this problem, the Commander Air Force, Pacific Fleet follows a practice of issuing advance logistic planning data in classified form based upon operational plans and impending aircraft deployments. Those responsible for support throughout the logistic cycle are thus given timely notice. This permits proper action to insure engine, component, assembly, and parts support of those craft by the time they are deployed, including the build-up of standard aviation "housekeeping" items.

Of course, the system is not perfect, and emergencies do still occur. Nevertheless, the idea and action are sound, the support is far better than it could be without such announcement of need, and the logistic operation remains fluid and flexible. By taking advantage of the full scope of "lead time," the system is more readily adaptable to fleet air operations.

It must be remembered that silence and the passage of time does as much to create logistic emergencies as do unforeseen operating developments. As often as not, when a demand becomes manifest initially, it is of low priority and can be met through normal processes. But if it is announced near the moment of need, it often must be processed as an emergency.

This suggests that it might be profitable to apply the Commander Air Force Pacific practice in contemplated deployments of other weapons, equipments and components, such as ordnance, communications, facilities, small boats, vehicles, hospital equipments, and others. By the release of deployment and construction plans in a form designed specifically for use by operating logistic and supply activities in developing planned requirements, theater logistics could be more flexible and "lead time" less critical as a limiting factor in naval operations.

*Communications:* Operational commanders are always aware of the need for keeping open their message circuits primarily for tactical purposes. Following this premise, the logistic elements do not use fast communications for the lower priority, routine supply operations. They work, instead, on a lead time formula which includes mailing time in passing requirements through successive logistic stages.

Although despatch facilities are not by any means denied logistic operators, the limitations of the communication system make it necessary to use despatch traffic primarily for the highest priority requirements. By virtue of the choice one must make between mailing processes and despatch communica-

tions, the "make known" portion of the lead time factor becomes generally established at the mailing-time figure. All subsequent action is paced to that medium, and despatches in logistics retain their status as special, out-of-the-routine procedures.

There is no question about *item* emergencies; despatch facilities for these are readily available. But the routine cyclical replenishment system and much of the interim requisition procedure are geared to the longer lead time factor. If a quicker logistic *pace* is to be established, therefore, it is submitted that fuller application of fast communications is a good place to start.

The whole process might ultimately be geared to a new rapid stride and become as routine as the working of a ticker-tape network in the financial world. The "making known" factor *in routine operations*, as well as in emergencies, could be reduced drastically if fast communications were applied across the board in naval logistics.

A study of the potentialities of radio communications as a routine supply-action medium is encouraging in terms of speed, simplicity, routing, and easy handling. The further possibilities of radio impulse hook-ups, with central automatic electrical machines, tape punch devices, selective routing and relay for supply action, tally computers, memory recorders, impulse activators, and other devices are indeed intriguing.[2]

Much of the in-transit time *between* logistic segments could be eliminated, the internal processing *within* segments could be reduced, many routine clerical evolutions might be eliminated, and the whole system might be brought to a fantastic pace by present standards.

To be sure, one finds a number of major problems such, for instance, as radio circuit availability, the enormous cost of developing a whole logistical communications network, and the ultimate dangers of enemy interference. Nor would the introduction of such revolutionary processes be easily applied without ample expert logistic planning. But on balance, and without minimizing the obstacles involved, the application of radio and electrical devices to logistical operations holds promise of considerable streamlining of the logistic process, with great reduction of the lead time factor.

*Processing Demands:* Requirements are processed through successive stages in the logistic cycle in accordance with established schedules based upon optimum operating conditions. The system is geared to a pace which is set on the basis of demand experience, past lead time factors, storage and carrier limitations, production time, monetary investment, criteria, and a host of other considerations. The logistical apparatus is thus on a well regulated cycle.

The important fact, however, is that "lead time," insofar as it is consumed by operational logistic evolutions, is the sum of these successive steps in the whole cycle. Thus, arbitrary cuts in the number of days allowed in a lead time schedule are likely to be squeezed through each evolution to be absorbed, if possible, by the last few steps in the process. The result may be incomplete, ill-considered, or wholly unresponsive action.

It is not uncommon, for example, for the purchasing activity to receive a requirement calling for delivery at destination anywhere from two to six weeks *prior* to the date the contracting officer received the directive to buy. Hence the attempt to shorten lead time and improve logistic response by timetable manipulations accomplishes little.

What is more significant, however, is that such actions often have the effect of disrupting the routine machinery as well. Obviously, with relatively few urgencies, the system is well able to absorb the "shock" of non-routine demands. However, when battle fronts erupt as, for example, Korea, the shock is more pronounced. Over protracted periods, the shocks become more difficult to absorb, urgencies become so frequent as to be practically routine, and truly routine demands are shoved progressively further into the background until consumers come to believe that only by the cry "Emergency" can they get any response at all. Thus a cycle is set in motion which only tends to weaken the system as a whole.

It is not difficult to imagine that in a big war, genuine exigencies are likely to multiply considerably, and if a faster logistic pace has already been falsely stimulated by arbitrary lead time cuts, operators will find themselves virtually spinning from one crisis to another, responding only when blasted from on high.

Although the recently implemented material priority system is a step in the right direction, in practice one finds that there are really only two paces maintained in logistic operations, and although not recognized as such, the measure of lead time tends to be expressed in terms of these two paces, namely, emergency and routine. There are no "half emergencies," no "routine emergencies," nor "deferrable routines." It is either all-out emergency, or it is routine.

This raises the question, then, whether more successful operation of the system as a whole would be better served by handling emergency requirements through other than routine machinery. If emergencies could be handled without disruption to routine operations, perhaps the latter could be improved. If, on the other hand, routine demands were processed at an accelerated pace through greater use of modern electronic and communications techniques, or be otherwise improved, there might be fewer "emergencies."

It is submitted, therefore, that only two paces in logistics should be recognized, namely, emergency and routine, and the channels for each should be separate. Instead of directing exigency requirements exclusively through normal routine channels, since emergencies are not confined to new demands requiring purchase action, a broadcast message to all major supply points in a theater or area might fill the

[2] See also, "Miracles Ahead in Telephone Age," *U.S. News and World Report*, 22 January 1954, pp. 62-70.

need more quickly than can be accomplished through "normal" channels.

Thus, for example, in the Pacific Ocean Area, if Subic needs something fast in an emergency, rather than follow regular channels which may see the items issued from a continental source, it might be as well to tap Japan, Guam, and Pearl Harbor at the same time. If any area agency has the item and the means for getting it to Subic quickly, a series of despatch responses with information to the others would be far less costly than premium supply action from the States.

There might be a number of objections to this arrangement, one of which would be that such diversions may leave the intermediate supplier in short supply, requiring the same emergency action to bring him up to level again.

However, such procedure would not necessarily require one activity to deplete itself to meet the emergency of another. Yet, even if it did, it is reasonable to assume that identical item urgencies will not generate everywhere, or even at two points, simultaneously. Thus in the replenishment of the depleted supplier, a routine interim resupply would in most instances cover him.

With good theater control such a procedure may prove far more flexible than are present arrangements, and in the event of a major war such flexibility might permit more rapid application of the principle of concentration. *Item* attention at higher staff levels would thus give way to *system* attention, and as procedures, channels, and media are improved, the items would tend to take care of themselves.

*Procurement Procedure:* It is through this function that the military finds the door to the vast reaches of our national economy, and, in passing through, one encounters a whole new universe of problems ranging from engineering and production capabilities to profit motives and politics.[3] In its singular role of operating within both the military and industrial orbits, procurement is quite properly steeped in statutory and administrative controls which tend to lengthen lead time sometimes to the point of exasperation.

The statutes provide for quick purchase action when a need is compelling and of unusual urgency. But the law also contains definite requirements to safeguard the public from abuses of government purchasing authority, and the essential need must be clearly shown.

Thus if purchase action is ultimately involved, the highest requisition priority and closest deadline may travel quickly through all logistic phases to the purchase stage only to be stopped there by the legal technicality of an inadequate justification for exigency contract action. Real though the emergency may be to the man in the fleet, if it does not fit the criteria for exigency purchase action when translated into terms of legal authority, valuable time can be lost in securing additional justification to prevent invalidation of a contract.

In the first six months of the Korean Campaign, for instance, operational emergencies of all kinds and degrees arose. But the interpretation of exigency authority under the procurement law was not uniform among contracting officers and their counsel. Thus the response at the purchase stage varied in direct relation to the liberality of application of the law.

Until recently, the services were operating under the full emergency powers of the law under a Presidential declaration of national emergency issued late in 1950. This authority is no longer available to the military departments. However, even though we are functioning at something less than full emergency conditions, the world situation today demands something more than was envisioned by insertion of the exigency section of the law in 1947.

It seems entirely appropriate, therefore, to broaden the exigency authority, in the absence of all-out emergency conditions, recognizing that we have not achieved the world tranquility we had expected in 1947. Coupling this with firm policy pronouncements and determinations, there would be a mandate for premium action at *all* logistic stages, including purchase, without hesitation, and the risk of extending "lead time" on the basis of legal technicalities could be reduced.

*Procurement Organization:* It is encouraging to note a wider appreciation of the gigantic business management problems involved in keeping our defense forces equipped with the finest and latest weapons. But the great emphasis that has been given to the purely *business* aspects of our logistic operations in recent years has tended to obscure the military aspects of the problem.

Thus, for instance, it is deemed advantageous to provide our commercial suppliers with a single point of contact within the military establishment in making contracts for certain commodities, by the assignment of purchase responsibility to one department for buying all the requirements of all the services.

What is often overlooked, however, is the very basic question of response to the individual military arms which are served by this system. From the standpoint of operating forces the channels through which demand documents must flow to reach the contracting officer become extended and time-consuming, the processes become rigid and inflexible where purchase functions are performed outside the control of the consumer, and "lead time" indeed becomes lengthened rather than shortened. The ultimate result is less logistic responsiveness.

At its base national defense requires combat efficiency and effectiveness by fighting forces. Thus, although broad political and economic factors must enter into questions of military procurement organization, such considerations should not preclude full examination of the effect of such arrangements upon the combat forces. Logistics is not an end in itself, and the quest for improved procurement operations

[3]VADM O. C. Badger, USN, "Problems of Command Logistics," Naval War College lecture, 31 August 1950, discusses some of the vital points of interest.

should not be pursued at the sacrifice of combat readiness and efficiency.

It is essential, therefore, that the benefits of modern weapons systems, combat experience, training, and sound tactical doctrine not be offset by a ponderous and inflexible logistic organization. If the interests of speed and reduced lead time are to be served, logistic organizations, channels, and working procedures must be kept as simple and direct as possible, and purchase functions, like all others, should be attuned to the pace and operating demands of the fighting arm it serves. Any other arrangement dooms the lead time factor to be longer than it needs to be.

*Delivering the Goods:* Consumers and suppliers alike are often likely to regard delivery time as a function of speed and distance, that is, so many miles traveled at a cerain average rate of speed will bring me my supplies in "X" number of days. But this ignores that intangible factor called "shipment waiting time," which sometimes is longer than the actual transport time.

With limited transport facilities, it is understandable that carriers must be operated according to schedules which cannot provide for the immediate pickup of each supply item as it becomes available for shipment. Thus a certain amount of waiting time is inevitable, and any lead time factor should, of course, include this period. However, unlike the mathematical considerations involved in weights, capacities, cubes, distances, and speeds in actual transport, this waiting time at the operating level is subject to a number of immeasurable and variable human factors.

In the fields of ocean and air lift we have agencies striving mightily to serve three demanding masters whose operational commitments must be met. With limited spaces, tight carrier schedules, urgent operational commitments, and heavy space demands from three prime users, the transport services are under rather constant pressure. The multiple influences thus brought to bear tend to force the service agencies to set their own pace and pattern of operations in order to render as equitable a service as is possible under the circumstances.

This can lead to such situations where, for example, a minor official is influenced to permit one service to offload the material of another in order to make room for its own supplies. This is merely part of the human factor, but the enormity of its implications in principle is disconcerting, for it illustrates violation of an old maxim of the management engineers regarding the difficulties of serving multiple masters. Again the question of fundamental logistic response arises.

The service agency, to be responsive at all, must almost arbitrarily establish its own norms and standards to give as good a service as it can to all comers. Shipment waiting time, a significant portion of the total transport time, can, under such circumstances, become a matter of pressure, aggravation, and misrepresentation of need, with the service agencies assuming the role of adjudicator between claimants. The military arms, therefore, have little means for deciding for themselves how best to utilize the limited facilities available to all.

By bringing pressures on already harrassed agencies for isolated "hot" items which are competing with equally urgent requirements of other services, we attempt to improve "lead time." But this helps only on individual items, and does little for the system as a whole. Thus the lead time "norms" and "standards" necessarily established by the service agencies should be kept under constant scrutiny and measured against the basic operating requirements of the forces they are designed to support.

Such are but a few of the areas which might be explored more fully in the search for more rapid logistic response. An important assumption underlying our defense effort today is that the United States cannot expect to have time to marshal its resources for months or weeks prior to our direct involvement in any future war. We must gain and retain a posture of military readiness which will permit immediate reaction and instant retaliation to attack.

Indeed, as greater powers for speed, range, and diversity are built into our defense machinery, the demand will be ever greater for speedier logistic reaction to operational requirements. In such an atmosphere, lead time will come in for some harsh scrutiny if it restricts our mobility and flexibility. Like the speedy halfback who can outrun any other member of his team, we must be careful not to let our tactical improvements run away from their essential support operations. We must not brake the development of new weapons and battle techniques. We must instead accelerate logistics and not weaken it by an incomplete understanding of lead time.

By the more judicious use of all the "lead" time available to us, fuller use of rapid communications and modern automation methods, recognition of two distinct paces and channels in logistics, refinements in procurement policy, application of military considerations in procurement organization, and constant re-examination of the responsiveness of service agencies, we may help logistics keep pace in an age of rocket speeds, atomic power, and astronomic distances and thereby reduce its limiting effects upon operations of the future.

# *HOW TO IMPROVE PROFITS— A CHALLENGE TO ENGINEERING*

**ACKNOWLEDGEMENT**

*Kenneth L. Block, Management Consultant, A. T. Kearney & Company of Chicago, is the author of this article. A condensed version of a paper presented before the Chicago Section of the American Society of Mechanical Engineers, it was published in the February, 1956, edition of "Mechanical Engineering."*

ONE OF THE MOST direct ways to improve profit is to reduce costs. The engineering department shares the responsibility for accomplishing this objective. This department can contribute to profit improvement by: (1) action which reduces costs in other departments; (2) action which reduces costs in the engineering department.

### REDUCING COSTS IN OTHER DEPARTMENTS

The basic manufacturing and/or procurement cost of any mechanical or electrical product is usually established by the time it leaves the drafting board. Regardless of the efficiency which tooling or purchasing manages to achieve later, the designer may have set limits beyond which relatively little improvement can be made. The total design effect on manufacturing costs may be as much as 35 per cent of the total material, labor, and burden cost. Therefore one of the basic responsibilities of engineering management is to show engineers how to apply economic principles to all phases of design. There must be a constant effort to simplify design in order to lower the cost of the product.

Low-cost methods of designing depend upon a wide knowledge of basic methods of manufacturing and of the specific machines and tooling in the particular company. Close supervision is required to insure that each part and product is engineered to minimum manufacturing cost compatible with required quality and performance.

*Design Rules.* Some good rules to follow in designing for low cost are as follows:

1. Design for maximum simplicity of all functional characteristics and sturdiness required in the end product.
2. Ask yourself, "Is it absolutely required?" If possible, eliminate the part or consolidate it with others.
3. Design for most economical production method consistent with quality and quantity of output required.
4. Select the lowest-cost material which will fit the foregoing requirements.
5. Design for minimum finishing operations.
6. Design for ease of holding and setting up or handling the parts.
7. Specify finish and accuracy to no greater tolerances than are necessary.

In an attempt to realize all possible savings in this area, some companies have set up a product-engineering group which adapts the original design to lowest shop costs consistent with necessary requirements for quality and quantity of output. Other companies have asked the manufacturing and purchasing departments to suggest changes in design which would save money through changes in process or the substitution of material.

*Service Life.* Some engineering departments have reduced the manufacturing cost of parts and subassemblies by insisting that each part and assembly be designed consistent with the service life of the end product. In one instance, where this principle was not kept in mind, an engineering analysis disclosed that parts and subassemblies used in a finished product with a life of 10 years were designed with probable service usage of anywhere from a minimum of two years to a maximum of 87 years. The excess life designed into some of the parts increased costs; the too-short life designed into other parts was bound to lead to customer dissatisfaction.

*Standardization.* Standardization of parts can reduce

costs in other departments. Some companies set up a "standard-parts book" in which they list permanent part numbers of commonly used parts, such as hardware and fittings. Management approval is required for design and use of any hardware or fittings not listed in this book.

Standard parts are purchased or manufactured in economic lot quantities and placed in stock. This saves the cost of separate purchase, receipt, inspection, and accounting on smaller purchase orders for a variety of special parts. It also saves shop-ordering cost, setup cost, and handling cost on manufactured parts.

*Maximum Tolerances.* The intelligent use of engineering tolerances can decrease the cost of a part and minimize scrap. The designer should always ask himself, "Would we have to scrap this part if tolerances were increased $\pm 0.001$ in., or $\pm 0.002$ in.?" If the answer is "no," he should incorporate these additional limits in his tolerances. It is especially important to keep tolerances loose for ease in assembly. Selective fitting on the assembly floor increases costs tremendously.

The statistical quality-control department is often of great help where close tolerances lead to excess cost and result in excess scrap.

*Engineering Change Orders.* Engineering change orders often increase the costs in other departments needlessly. Changes are generally issued to correct an engineering error, to reduce costs, to simplify manufacturing, or to improve serviceability. Many changes are made without adequate analysis of the cost of disposing of obsolete inventory and tooling. Changes should be put into effect only if the over-all cost and savings picture is favorable, or if they affect safety or the reputation of the company.

### REDUCING ENGINEERING-DEPARTMENT COSTS

The previous section has pointed out ways in which the engineering department can be instrumental in effecting savings in the shop, purchasing, tooling, production control, cost and accounting, inspection and industrial-engineering departments. There are many ways in which the engineering department can reduce costs through proper organization and administration of its own department.

*Organization.* The engineering department should be organized so that work will be completed on time and at the lowest possible cost within the department. Proper organization structure depends upon the size, function, and personalities of the engineering department. In general, however, the service activities should be separated from the design and production engineering activities. Reduction in cost can often result from proper utilization of technically qualified design engineers on design work and less technically trained people for service work.

*Planning and Scheduling.* Low-cost operation of an engineering department calls for proper planning and scheduling of work. The time to complete each engineering project should be estimated in advance and compared with the manpower hours available during calendar periods by specific types of engineering work. This determines whether the requested data for the project can be met. If this is impossible on a normal basis, it is necessary to take corrective action through overtime work, subcontracting of engineering work, or the addition of more engineers.

A report should be issued at the end of the project showing the actual hours expended on the job related to the estimated hours. The validity of the estimate can be easily checked and corrective action taken in regard to future estimating.

But usually this action is not enough for proper control. We want to know as soon as a job starts to over-run the estimate so that corrective action can be taken while the project is in process. This action is accomplished by relating the hours actually expended to date to the percentage of completion of the job applied to the estimated hours. If actual hours are greater than estimated hours, investigation should be started immediately to determine the reason why, and whether corrective action can be instituted.

If the estimate for the project is an addition of separate estimates by specific jobs or types of work within the project, actual hours expended should be gathered on the same basis so that a more exact picture can be gained as to where the project is overrunning. Some companies use a visual graph to plot actual progress against scheduled progress for each job as of the current date. This is used as an aid in controlling the cost of the project.

*Cost Controls and Budgets.* One of the best ways to determine the engineering cost of any project is to use a time-charge system which will allocate every hour of each engineer's time to a proper breakdown within each project. These hours, multiplied by the engineering cost per hour of the engineer's time plus engineering overhead allocated to those hours, give an accurate breakdown of the total cost of the job or the cost of any part of the job. This engineering develops a backlog of information useful in estimating the cost of new projects.

*Personnel Control.* Employee efficiency is directly proportional to employee morale. Therefore an intelligent engineering-personnel program is necessary. Such a program should include provisions for simple practical methods of procurement, the handling of complaints and terminations, the asignment of personnel to operating programs, the maintenance of history records, and the administration of wages and salaries.

Proper salary administration which is based upon job evaluation, as well as periodic reviews of job performance by the supervisor, his superior, and the engineering-department personnel manager, help greatly to insure increased morale within an engineering department.

*Standards.* Several types of standards can contribute to efficient operation of the engineering department: An engineering-procedures manual, a drafting-room

manual, a design handbook, and a standard-parts book.

The engineering-procedures manual usually specifies the detailed procedures in use within the engineering department. These include policies and rules relating to working hours, vacation policy, rules of discipline, and other matters. Once a particular policy or procedure is written, it is easier to assure the conformance of the entire department.

A drafting-room manual describes company drafting practices. It is confined to information which the draftsman will require frequently and includes data on materials, design data, conversion tables, processes, and finishes.

The design handbook states the desired design methods for products manufactured by the company based upon equipment which is available within the company.

A standards book utilizes standards set up by government, industry, and commercial associations, and by the company itself. It specifies adherence to these standards. The establishment of a standards-parts book reduces cost by eliminating repeated detailing of small utility parts used in many designs by a particular company. Creation of design standards for items such as fastener installations, electric wiring, assemblies, conduit assemblies, and sheet-metal cutouts eliminates the constant repetition of extensive drawing notes and dimensioning.

*Simplified Drafting.* Engineering drawings can be simplified by eliminating nonessentials, simplifying delineation, and stripping all frills which do not result in a loss of clarity or accuracy. In some cases this approach has reduced engineering time from 20 to 30 per cent.

# EFFECT OF TURBINE ENGINES ON AIRCRAFT DESIGN

**ACKNOWLEDGEMENT**

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GAS TURBINE aircraft are most economical if they fly fast, and from this fact stem most of the special features of turbine-engined transports. This paper begins with a description of the kinds of gas turbine engines used in aircraft, and then shows briefly why such airplanes do fly fast. Finally, a rather more detailed account is given of three design problems of special interest. To avoid tedious repetition, it should be said at once that many of the statements made need to be qualified by reservations and exceptions, which have been omitted in the interests of clarity and brevity.

## TURBO-PROP VERSUS TURBO-JET

Common to all aircraft turbine engines is an arrangment of air intake, compressor, combustion zone, and primary turbine constituting the gas generator (Fig. 1). The output of the gas generator is a stream of gas possessing available energy in the form of heat, pressure and velocity. This energy derives from the heat energy released by the fuel burnt, and the thermal efficiency of the transformation depends on the engine design. Good thermal efficiencies require efficient components, a high working temperature, and a high pressure ratio. Some of the latest engines have two independent axial compressors in series, each driven by its own turbine (Fig. 1*b*). Such engines are said to be of two-spool design, and can use higher pressure ratios than single-spool engines. In forward flight, some initial compression is obtained by slowing down the air entering the intake, so that the thermal efficiency improves with increasing forward speed.

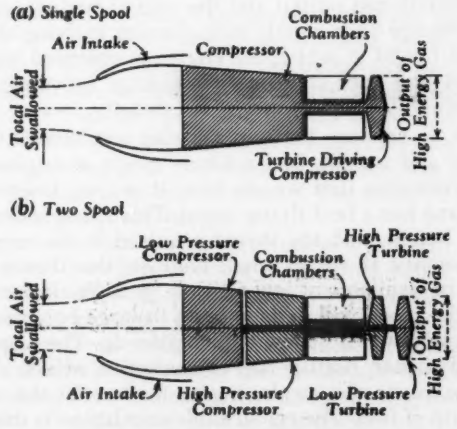



**Figure 1. The gas generator.**

The different types of turbine engine are distinguished by the means employed to convert the gas energy into useful work in propelling the aircraft. The simplest method is to employ a nozzle designed to eject the gases with the greatest possible momentum (Fig. 2). The resulting engine—the turbo-jet—is the simplest, lightest and most compact of the gas turbine family, but the efficiency of conversion of gas energy into thrust is low because of the large

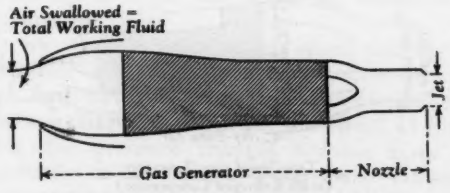



**Figure 2. Diagram of turbo-jet engine.**

amounts of kinetic energy wasted in the high-speed jet. The efficiency improves with increase of flying speed, which is one reason why it is economical to fly fast on turbo-jet engines.

Another way to improve propulsive efficiency is to reduce the exit velocity of the jet. This can be done by accelerating a larger quantity of air to a lower velocity. In this way the thrust, which is measured by the change in momentum, can be maintained, while the wasted kinetic energy, which is measured by jet speed squared, can be reduced. In the turbo-prop engine, energy is extracted from the jet by additional turbine stages and used to drive a conventional propeller (Fig. 3). The total air flow may be increased a hundredfold and the result is an engine in which greatly improved fuel consumption and take-off thrust are obtained at the expense of increased weight and complication.

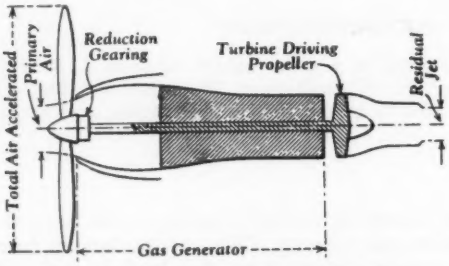



**Figure 3. Diagram of turbo-prop engine.**

### BY-PASS ENGINE

There is a range of compromise engines between the turbo-jet and the turbo-prop. The simplest of these is the by-pass engine (Fig. 4), in which part of the main compressor is enlarged, and the extra air is mixed with the primary air in the exit nozzle. The method is restricted by practical limitations of compressor and turbine design, and by-pass engines closely resemble jet engines in their characteristics. Small, but worthwhile improvements in fuel consumption and take-off thrust are obtained at the expense of increased engine size.

The ducted-fan engine is a development of the by-pass engine in which reduction gearing is introduced into the drive to the enlarged compressor. It would be possible to design such an engine to have characteristics anywhere between the turbo-jet and turbo-prop extremes, but current thinking suggests an engine in which the air mass flow is roughly trebled. Such an engine remains a close relative of the jet engine, and it is probably an ideal engine for transports in the 500 to 550 miles per hour class. Because of lack of ducted-fan engine development, these airplanes are now proposed with jet engines, and it is entirely possible that owing to their late start, and the comparatively small gains they offer, ducted-fan engines will be altogether lost as a type.

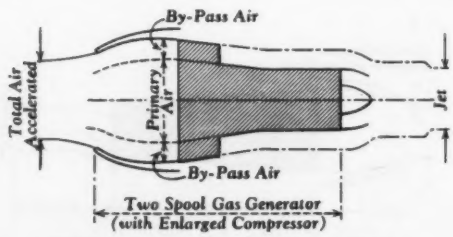



**Figure 4. Diagram of by-pass engine.**

Another intermediate class of engine has recently been announced. This has been called a "supercharged turbo-prop." It is a two-spool engine in which the airscrew and power transmission are of normal size, but the gas-generator is unusually powerful. The result is a lightweight turbo-prop engine with a high power output at cruising speed and height. Fig. 5 is a rough indication of the cruising speeds and altitudes suitable for airplanes fitted with these engines.

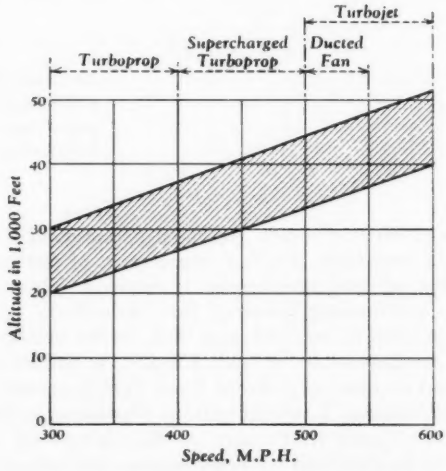



**Figure 5. Cruise speed and altitude relationship.**

### OPTIMUM HEIGHTS AND SPEEDS

The design of a succesful turbo-jet transport is an exceptionally difficult business, but it so happens that the main forces that drive the designer are easily understood. It is a characteristic of the jet engine that the thrust output and the rate of fuel consumption change quite slowly with changes in flying speed. If the height at which the engine is operated varies, thrust and fuel consumption change together, and are roughly proportional to air density.

Let us suppose that we have an airplane of fixed shape and weight, and a whole range of engines of different sizes that we can fit in it. At any height the airplane has a best flying speed. This speed increases with height, and the thrust required is the same at all heights. If we fit small engines, the thrust will only be available at low altitude, in high air density, and the speed will be low. If we fit large engines, the same thrust will be available higher up. The airplane will fly faster, but the fuel consumption will be about the same, so the airplane goes farther on the same amount of fuel. The remarkable conclusion is that by fitting larger engines the speed and fuel economy im-

prove together, and roughly at the same rate, which turns out to be as the square root of the engine size. There is a limit to this process, which is reached when the flying speed is so high that the drag of the airplane starts to increase because of compressibility effects. This speed is likely to be between 500 and 600 m.p.h.

The cruising speed then is fixed within fairly small limits, and this fixes cruising height for a given shape of airplane. The cruising height for the same cruising speed can be altered by changing the wing loading. If the wings are made smaller, the appropriate height will come down, and smaller engines will then provide the thrust. The choice of cruising altitude is finally settled by the take-off and landing conditions. Short airfields mean big wings, big engines, and a high cruising altitude; long airfields mean small wings, small engines, and a lower cruising altitude. With airfields of the present size, the cruising altitude comes out at about 40,000 ft.

To summarize this section:—(i) For economy, turbo-jet aircraft must cruise as fast as possible; the limit is set by compressibility. (ii) To cruise fast, and operate from normal airfields, turbo-jet aircraft must fly high.

### TURBO-PROP TRANSPORT DESIGN

Turbo-prop airplanes are under no compulsion to fly fast or high, but with conventional wing loadings they must fly high if they fly fast. Speed can be had at the cost of increased engine weight, and with engines of current design, cruising speeds between 350 m.p.h. and 400 m.p.h. seem best. The "supercharged turbo-prop," will lift this to about 500 m.p.h., when compressibility effects on airscrew tips may introduce a limitation.

The design conditions are less clear cut than in the turbo-jet case, and represent a balance between weight of engines and the economic worth of speed. A high cruising speed has sound economic value, the principal reasons being passenger appeal, and the simple fact that rate of earning is proportional to mean flying speed. If we take a conventional wing-loading of, say, 80 lb. per sq. ft., we have a fixed relationship between best flying speed and height, just as in the turbo-jet case. The gas-generator size varies nearly as the cube of the cruising speed, instead of the square of the speeds as in the turbo-jet case, and the take-off power output soon becomes unnecessarily big. It is therefore proposed to limit the size of the power side of the engine—heavy items like the reduction gearing and the airscrew—while the gas-generator size goes on increasing. The result is the "supercharged turbo-prop."

The implications of this development are still being worked out. The cruising power, and hence the economical cruising speed, can be increased for quite small changes in engine weight, and these changes are predictable. Airscrew efficiency is affected by fast cruising because the blades are traveling faster along their helical paths than the wing moves along its straight one, and so the blades enter the compressibility zone before the wing does. These changes are reasonably predictable, and are being steadily postponed to higher and higher speeds. When these effects, and many others such as the change in thermal efficiency with flying speed, are taken into account the conclusion is that we can make a turbo-prop airplane lighter for a given task than a turbo-jet up to about 550 m.p.h. cruising speed.

This result is so surprising that one looks for the snags. The first of these is that turbo-props of the right kind are not yet available. Turbo-jet development has out-stripped turbo-prop development and it will be three or four years before the comparison I have made will be valid. The second difficulty is noise. To a ground observer, turbo-prop airplanes are very quiet, and turbo-jet airplanes almost unbearably noisy. Inside the airplane, it should always be possible to make a turbo-jet airplane quieter than a turbo-prop, because the airscrews are inevitably a source of noise and vibration. Both can be made quieter than piston-engined airplanes, and better than most forms of surface travel but it is difficult to be sure if this will still be true for turbo-prop airplanes cruising at more than about 500 m.p.h. Until we can be sure, we do not know whether turbo-prop airplanes will stop at 500 m.p.h. cruising speed, or rival turbo-jets over the whole speed range.

There remains a further consideration. The turbo-jet engine is simpler than the turbo-prop and much of the extra weight of the jet airplane is fuel. It can be argued that fuel is cheaper than engines, and on these grounds, the jet airplane can be defended against its lighter, more efficient, but more complicated turbo-prop competitor. The struggle between turbo-prop and turbo-jet divides the aircraft industry on both sides of the Atlantic, and I have mentioned only a few of the points under debate.

The remainder of this paper deals in more detail with three design problems which I have selected. They are: wing design, which is affected chiefly by the high cruising speed; certain lift aids, which are made practical by turbine engines; and pressure-cabin design, which is a problem arising from high flying.

### WING DESIGN

Piston-engined transports, especially the long-range ones, all have very similarly shaped wings. The aspect ratio (ratio of wing span to mean chord) is usually about 10, and the average thickness of the wing is usually about 15 per cent of the chord. Such a wing is very suitable for present-day turbo-prop airplanes such as the Viscount and the Britannia and for speeds up to about 420 m.p.h. no better wing shape is known.

If we try to push the cruising speed still higher we encounter what are known as compressibility effects, a term covering a large class of phenomena. The cause is simple enough. As the speed of flight increases, the pressure changes become more intense, initially as the square of the speed. At some speed, depending on the shape of the object in question, the pressure changes are big enough to make

appreciable differences to the local air density—the air becomes compressed—and peculiar things happen to the airflow. Shockwaves form above the wing, and the airflow separates from the wing surface instead of sliding smoothly over it. The drag increases, and there may be vibration and loss of control.

Analysis of these changes is excessively difficult, although much can be learned from high-speed wind-tunnel tests and the initial stages are mathematically predictable. The result, as far as this paper is concerned, is that the wing design must be changed before the cruising speed can be increased. The most straightforward change is to make the wing thinner. By reducing the wing thickness to about 10 per cent of the chord, the cruising speed can be raised to about 500 m.p.h., and this may prove a very suitable wing for the next series of turbo-prop airplanes.

Most of the big jet airplanes, bombers and transports, rely on sweepback to postpone the bad effects of compressibility to a high speed. Sweepback does this, but it brings with it a crop of additional problems connected with structural design, and with the stability and control of the airplane. A mass of literature, bewildering even to the expert, exists on these subjects, and new reports are being published all the time.

The state of mind of the aircraft industry itself is revealed by Fig. 6, which shows a selection of the wing planforms that have been proposed for large turbo-jet airplanes. It should make us very humble. A class of 12 year-olds would produce similar results in half-an-hour, and the uninformed must surely assume that these shapes have been light-heartedly tossed off as the expression of their chief designers' artistic feelings. In fact, five of the six have been sufficiently well supported to be built, at great cost. They are the outcome of thousands upon thousands of hours of hard thinking and hard testing. They have survived competitive and sometimes bitter, technical argument and scrutiny; they all work, and no one is sure which is best. The variations arise because the design requirements conflict, and different design teams have varied the emphasis. We could not trace all the arguments in a year, but we can try to guess at the chains of reasoning leading to a few of the shapes, and this will have to serve.

One line of argument runs like this. A long, narrow wing—of high aspect ratio—is efficient, and sweepback raises the permissible cruising speed. These are good things so we will have them both. It helps the structural design to place the engines well out along the span to relieve the bending due to the wing lift, and a clever designer has found that by hanging the engines below the wing on stalks he can improve the flying qualities. The result is airplane A in Fig. 6. Inspection of this suggests that it would be a much "cleaner" airplane if the engines were buried in the wing. This makes the wing thicker, at least locally, and to preserve the high cruising speed we must increase the sweepback and the wing chord. It is convenient to make the wing biggest at the roots, but then the engines, with their intakes and jet pipes,

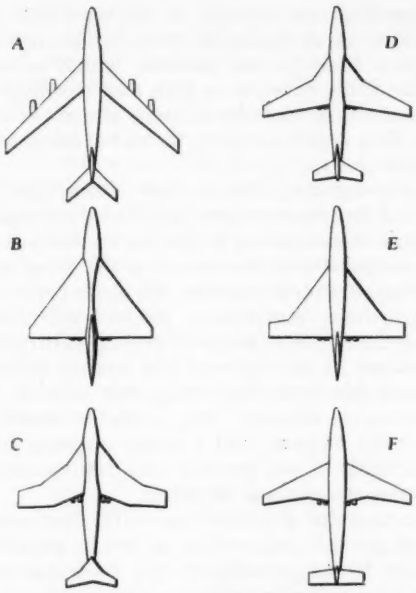


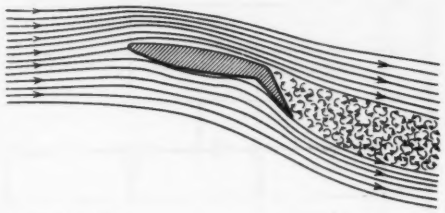

**Figure 6. Wing planform design.**

drive tunnels through the wing structure. This is serious if the wing has a big span but does not matter if the wing has a low aspect ratio and sharp taper. Such a wing is light in weight but aerodynamically inefficient because of the small span. There is a way out. By going to the limit (airplane B in Fig. 6), it becomes possible to dispense with the tail and make a beautifully clean delta-winged airplane with buried engines, no tailplane, and only a rudimentary body. These are extremes. There is a range of intermediate solutions, while design E aims at preserving the good features of the delta while improving the inefficiently small span.

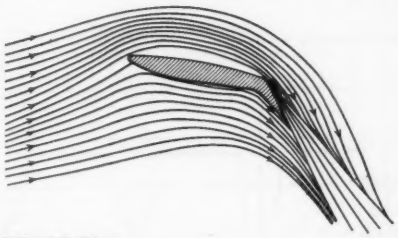
This is the disappointing story of our attempts to design wings for airplanes flying a little slower than the speed of sound. For supersonic transports it is possible only to guess. The indications are that supersonic transports, to be economical, will have to be very fast indeed; not just a little faster than sound, but three times as fast. They will cruise at least 10 miles high, and they will almost certainly have wings of small span. These wings, it seems, should be either straight or very much swept—perhaps in the form of a narrow-angle delta like a paper dart. These are guesses, but one thing is certain, their speed will be wasted unless the terminal arrangements keep pace.

### LIFT AIDS

It has been known for many years that profound changes in the pattern of airflow around a wing can be triggered off by injection of compressed air. Fig. 7*a* illustrates the air flow around a wing with a trailing-edge flap deflected. The purpose of the flap is to increase the wing lift, which it does; but its effectiveness is reduced by the separation of an eddying wake from its upper surface, so that the gain in lift is less



a Airfoil with Flap



b Airfoil with Flap and Air Injection

**Figure 7. Flow over airfoil with flap.**

than theory predicts. This separation can be prevented by a jet of air over the top of the flap, Fig. 7b, and the full theoretical lift increment might then be expected.

Fig. 8 shows that the air injection does indeed eliminate the loss, and adds some additional lift as well. This additional lift is due to a phenomenon known as super-circulation, and may be undertood by supposing that the air jet entrains additional air from the main airflow, and accelerates it. The well-known Bernoulli theorem states that when the speed of a fluid is increased its pressure falls. The result is that the pressure over the top of the wing is reduced because of the acceleration produced in the main air flow, and this accounts for most of the extra lift. The two kinds of lift that air injection produces are quite different in character. The first kind, due to elimination of the air separation, is obtained quite economically, but it is limited in quantity. The second kind, due to super-circulation, is expensive but can be had in large amounts—several times the normal wing lift —if one is able and willing to pay the price in power.

One fascinating possibility is an airplane that can fly in its own slipstream. All airplanes with propellers gain additional lift because of the increased airspeed over the portion of wing behind the airscrews. It would be possible to design an airplane with lightweight turbo-prop engines, large flaps, and air injection which would be capable of hovering without the use of rotors. Control would be difficult, but such an airplane could be a rival to the transport helicopter. Immediate applications will be less ambitious. Air injection applied to an otherwise conventional airplane can be used to reduce the landing speed, and so improve safety and regularity in bad weather. It also reduces the speed required for take-off, but this does not always pay because the loss of engine power is usually enough to cancel out the gains. The "supercharged turbo-prop" is an exception here, because it has gas-generator capacity to spare for air injection.

Air injection is not the only way to control airflow. Strangely enough, sucking will do instead of blowing, and the turbine engine can be made to do this instead. Suction to improve lift uses less power than blowing does, but it is less positive in action, and the possible gains are smaller. Suction can be used to reduce drag as well as improve lift, and in fact it offers all sorts of fascinating possibilities which have tantalized designers for years without ever quite coming into fruition. If suction is more delicate than air injection, jet deflection is more brutal. It is nothing less than turning the main blast of the jet engines downwards. If the engines are sufficiently powerful the whole aircraft may be lifted bodily, but transport airplanes cannot use such big engines unless they fly very high indeed, and then, of course, they could take off and land quite well in the normal way. As usual, moderation is more likely, and this takes the form of deflecting the jets downwards at an angle, so that the weight is only partially supported by jet deflection. The take-off and landing are then normal in appearance, but slower.

All these devices for making airplanes fly more slowly increase the difficulty of providing satisfactory control, and if this is not dealt with the pilot's job might get more difficult instead of becoming easier. Fortunately, air injection improves control effectiveness; and this will probably be enough for all moderate applications of these new lift aids.

### PRESSURE CABINS

At a height of 8,000 ft. the air pressure has fallen to 10.92 lb. per sq. in., about 74.2 per cent of its value at sea-level, and this is acceptable. Passenger-carrying airplanes flying higher than this are pressurized, and the cabin structure must be designed to withstand the pressure difference. Fig. 9 shows how this varies with airplane altitude. A pressure difference of 10.92 lb. per sq. in. is enough to maintain 8,000 ft. cabin altitude at any height whatsoever.

It should not be thought that pressure cabins are novel, or peculiar to turbine-engined airplanes. All the long-range passenger airplanes in use today are piston-engined, and all are pressurized. The pressure

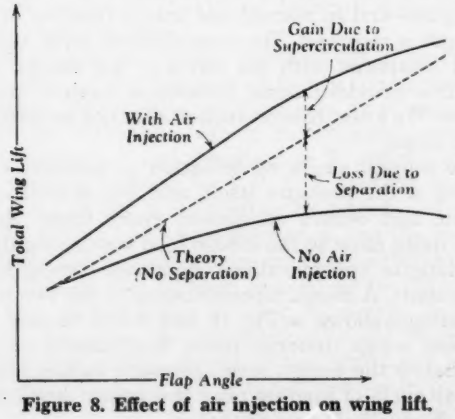



**Figure 8. Effect of air injection on wing lift.**

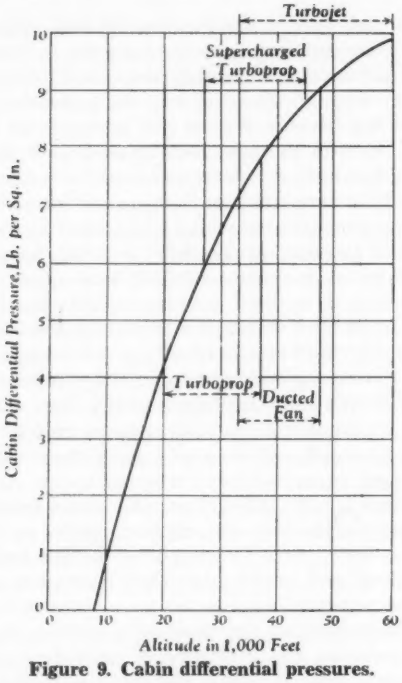



**Figure 9. Cabin differential pressures.**

difference of 7 to 8 lb. per sq. in. is suitable for turboprop airplanes, and 8 to 8½ lb. per sq. in. is sufficient for turbo-jets, so that turbine-engined airplanes are not very different in this respect from the latest types of piston-engined aircraft. Nevertheless, the pressure cabin is an essential part of the turbine-engined transport and the associated structural problems must be solved. Most people have heard of "high level" fatigue and know that it is a disease to which pressure cabins are subject.

Metal fatigue is not novel either, several disasters have been attributed to wing fatigue failure. It is reasonable to inquire if there is some fundamental difference between pressure-cabin design and wing design which makes one problem more acute than the other. The difference lies in the type of loading to which these items are subjected. A wing is designed to withstand the most extreme loading it is likely to encounter—for example, a severe maneuver or a violent gust—and in normal use only a fraction of this strength is required. The normal stress level, then, is small compared with the stress at the design load, and this provides some protection against fatigue failure. We know this protection may not be sufficient but it helps.

The biggest single contribution to pressure-cabin loading is the pressure itself, and this is controlled, known, and occurs on almost every flight. Something quite close to the design load occurs regularly, and fatigue considerations dominate strength requirements. A rough representation of the two kinds of loading is shown in Fig. 10, and it will be seen that whereas wings undergo many fluctuations of load well below the design level, pressure cabins have a regular cycle of loading near the design level, with small fluctuations superimposed.

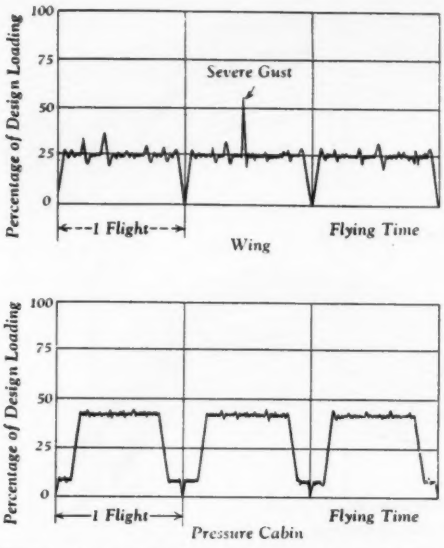



**Figure 10. Loading diagrams for cabin and wing.**

Pressure-cabin structural design, then, is principally a matter of fatigue, and we know that in securing a good fatigue life it is important to avoid structural discontinuities, such as notches, cut-outs and changes in thickness. Such cut-outs have been studied and it has been found that, by careful shaping of the holes and suitable reinforcement around the edges, their bad effect can be minimized. The success of these adaptations is measured by the "stress concentration factor," which is the ratio of the maximum stress in the neighborhood of the cut-out to the stress in the unperforated sheet. Perfect design, in this sense, would give a stress concentration factor of one.

A suitable analogy is a pneumatic tire. As normally inflated, such tires leak when puctured, but the damage does not spread. An over-inflated tire may split or explode if punctured, and so may a normally inflated tire if the initial damage is a sufficiently large cut. Pressure cabins may behave in either of these ways. A cabin of very efficient structural design is usually of the explosive kind, but may be acceptable with certain safeguards. If carefully maintained it should give a long period of safe service, and its eventual failure from fatigue can be forestalled by insisting on its replacement after a prescribed period of use.

Without doubt, a high standard of safety can be obtained with this type of pressure cabin, but the more attractive idea of a pressure cabin that will "fail safe," that is, leak harmlessly, is the subject of an increasing amount of research. Cabins of this kind are heavier, and this fact must be accepted. Two questions are of great importance. The first relate to the alloys of construction; metallurgists are asked to provide materials with properties not previously emphasized sufficiently—ductility, fatigue life, and resistance to tearing. The second is the general question of just how to design structures which fail safe, wherever the initial damage may happen to be located.

# THE PROPERTIES OF MATTER AT HIGH PRESSURE

**ACKNOWLEDGEMENT**

*This is a slightly abridged version of the Forty-second Thomas Hawksley Lecture, delivered by Professor D. M. Newitt, Head of the Department of Chemical Engineering, Imperial College of Science and Technology, South Kensington. It was presented to The Institution of Mechanical Engineers on 18 November, 1955, and was published in the January, 1956, edition of "The Chartered Mechanical Engineer."*

In almost every branch of technology today, research is being directed towards extending the boundaries of operating conditions by the introduction of new or improved experimental techniques, by theoretical studies leading to more accurate design procedures and by the use of more robust materials for plant construction.

In some instances, as for example in steam raising, the effort takes the form of stepwise increases in working temperatures and pressures, leading to predictable improvements in cycle efficiencies. In others, as for example in exploring the structure of matter, the immediate objective is the attainment of temperatures and pressures likely to bring about an overlapping of the electron phase spaces; to the end, theory suggests that pressures far in excess of any yet realizable in the laboratory are required, and it may be that entirely new methods and techniques will have to be discovered before the predicted values can be reached. In such circumstances, a close collaboration between the physicist and the engineer would seem to afford the best prospect of overcoming some of the formidable difficulties which are to be expected when advancing on this frontier.

It is my purpose in this lecture to give some account of the characteristic properties associated with highly condensed systems and highly stressed materials, as revealed by work carried out during recent years. It may be well at the outset to have in mind the order of pressures with which we shall be concerned. At the lower end of the scale is a pressure domain in which the behavior of a fluid is determined largely by a balance between the short-range repulsive forces and the long-range attractive forces of its atoms or molecules. At temperatures not too far removed from room temperature, this domain may extend up to about 50,000 bars,* after which it seems probable that the liquid state will cease to exist. The second domain, which overlaps the first and extends to some $10^6$ bars, is one in which solids in general undergo polymorphic transitions, giving rise to a series of stable phases of progressively increasing density. Thus, over a range of pressures of 20,000 bars, ice has been shown to exist in seven different forms. The third domain is one extending from about $10^6$ bars upward, and defines conditions in which on theoretical grounds it is expected that a break-down in the structure of matter will occur. It may be recalled that pressures of this order are postulated at the center of the earth and in many of the stars.

At the present time, it is practicable to operate industrial plant at pressures up to 3,000 bars, provided the working temperature is not too high. In the laboratory, it is comparatively easy to experiment at 15,000 bars over a temperature range of several hundred degrees, while a limited amount of systematic work has been done at pressures as high as 100,000 bars. This probably represents the extreme limit attainable by the use of existing materials and methods of plant construction.

*1 bar = 0.987 atm. = $10^6$ dynes per sq. cm. = 14.5 lb. per sq. in. = 0.9807 kg. per sq. cm.

## THE PRESSURE-VOLUME-TEMPERATURE SURFACE

In studying the behavior of highly condensed systems, the thermodynamic functions most amenable to accurate measurement are the two intensive quantities, pressure $P$ and temperature $T$, and the extensive quantity, volume $V$. A $P, V, T$, surface, such as that shown in Fig. 1, will define the boundaries of the various phases of a single substance, and the regions in which two or more phases are in equilibrium; and planes cutting the surface parallel to the axes will give the corresponding isobaric, isometric, and isothermic diagrams. To engineers, who are concerned largely with energy changes, other graphical representations, such as the temperature—entropy and the various Mollier diagrams may be more familiar.

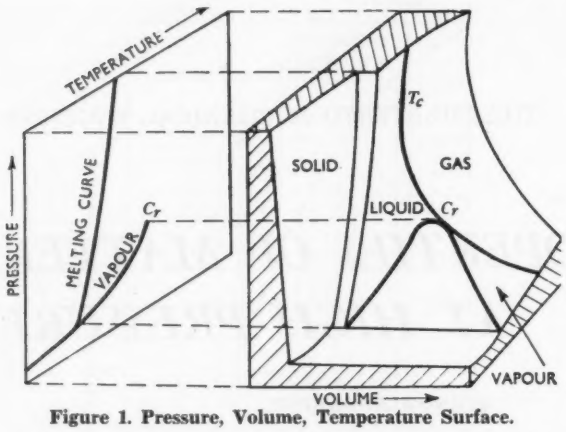



**Figure 1. Pressure, Volume, Temperature Surface.**

In Fig. 1, the solid, liquid, and gas phases are represented by smooth surfaces extending indefinitely along the pressure axis. This is undoubtedly an oversimplified picture, since it is known that most, if not all, substances undergo polymorphic transitions in the solid phases, and there is the possibility of an upper boundary to the region of coexisting liquid and solid. Both liquid and vapor may also exist in more than one phase.

The data at present available for the construction of $P, V, T$, surfaces usually take the form of measurements of compressibility or of isothermal or isenthalpic expansions; they are of varying degrees of accuracy and, in general, any particular set of observations covers only a small area of the $P, T$ plane. The manipulation of such miscellaneous data to give internally consistent diagrams is, in consequence, a laborious and time-consuming task; and it is only recently that a systematic survey and analysis of all the existing data for the more important industrial gases has been undertaken by the Mechanical Engineering Research Laboratory.

The surveys so far completed reveal few or no data outside the temperature range, —100 to 400 deg. C., or for pressures beyond 3,000 bars. Even within these limits, the data are in no case complete and not always consistent; in attempting to construct working diagrams, it is, therefore, necessary arbitrarily to weight the various sets of observations, and to interpolate by means of empirical equations. This situation is far from satisfactory, when the diagrams are required for design purposes, and the urgent need for a revision and extension of the data needs little emphasis. In this connection, it may be of interest to refer to some work now in progress at the Imperial College of Science on the $P, V, T$, surface of steam.

### THE PRESENT STATUS OF THE STEAM TABLES

The systematic investigation of the thermodynamic properties of steam was commenced at the beginning of the century by the late Professor H. L. Callendar and some aspects of his work formed the subject of the sixteenth Thomas Hawksley lecture which he delivered in 1929. Callendar's outstanding contributions in this field were the introduction of platinum thermometry and continuous-flow calorimetry, which formed the basis of his experimental methods for the determination of specific heat and enthalpy. He employed a simple and thermodynamically consistent set of equations to express his results which were published in the form of steam tables in 1915, 1924, and 1931.

Meanwhile, an International Steam Table Conference convened in 1929 assumed sponsorship for an extensive program of work on steam, which had been undertaken some years earlier as a collaborative effort by investigators from Czechoslovakia, England, Germany, and the United States of America. The results of this work were reported (Third International Conference on Steam Tables 1934) at the third conference held in 1934, and may be summarized as follows:

(1) A careful comparison of the international and thermodynamic scales of temperatures from 0 deg. C. to the sulphur point (National Bureau of Standards);

(2) A redetermination of the specific heat of water between 0 and 100 deg. C. (National Bureau of Standards);

(3) Three independent determinations of the saturation line:

(*a*) from $P, V, T$, data by F. G. Keyes (estimated accuracy 1 part in 1 to 2,000),

(*b*) from $P, V, T$, data by N. S. Osborne (estimated accuracy 3 parts in 10,000), and

(*c*) from $P, H, T$, data by A. C. G. Egerton and G. S. Callender (estimated accuracy 1 part in 1,000).

These three sets of data are in agreement up to within 4 deg. C. of the critical point after which they differ widely. An estimate of the differences is difficult to make, owing to the results being presented sometimes as experimental figures and sometimes as smoothed curves;

(4) Three investigations in the superheat region:

(*a*) $P, V, T$, data by Keyes extending to 360 atm. and 460 deg. C. (estimated accuracy 1 part in 1,000),

(*b*) $P, H, T$, data by Egerton and Callender extending to 360 atm. and 550 deg. C. (estimated accuracy 1 part in 1,000), and

(*c*) $P, H, T$, data by J. Havlicek and L. Mishovsky to 400 atm. and 550 deg. C. (estimated accuracy 1 part in 350).

Once again, owing to different methods of presentation, intercomparison of results is difficult, but, in general, there are significant variations in the values of enthalpy, with Keyes' results being the highest and Egerton and Callendar's the lowest, the difference being greater as the temperature increases;

(5) Two independent investigations of the latent heat of steam up to 365 deg. C., in the pressure range 100–200 atm.

(6) Joule-Thomson coefficients by H. Davis and R. Kleinschmidt, in the range 1–40 atm. and 125–350 deg. C.; and

(7) Specific heat data by W. Koch up to 250 atm. and 360 deg. C.

Based upon a careful assessment of this data, the Conference prepared International Skeleton Steam

Tables, with agreed 'tolerances,' for comparatively large pressure and temperature intervals, the upper limits being 350 atm. and 550 deg. C. From these Tables, a number of more detailed International Steam Tables have since been published, which, although differing one from the other, all come within the tolerances laid down by the Conference.

On the temperature-entropy plane, the areas covered by the experimental data referred to above are shown in Fig. 2. It has been pointed out by Keyes and Keenan (1955) that the accuracy of the data upon which the International Skeleton Tables are based is confirmed by the test of thermodynamic consistency, when the test is carried out employing the results of recent experimental comparisons of the international and thermodynamic temperature scales. There is, however, an urgent need for additional data, extending beyond the range of the Skeleton Tables, for boiler and turbine design, and it is hoped that a renewal of the collaborative effort that proved so successful in the past may be found possible.

Since the 1934 Conference, the results of several important investigations in this field have been published. Moser and Zmaczynski (1939) have made accurate measurements of the vapor pressure of water from 73.5 to 128.6 deg. C., and Kirillin and Rumjanzer (1950) have obtained $P$, $V$, $T$, data over the range 92–524 atm. and 430–600 deg. C. Some preliminary $P$, $V$, $T$, data, extending to 2,500 atm. and 1,000 deg. C. has also been reported by Kennedy (1950).

Furthermore, the British Electrical and Allied Industries Research Association has sponsored a program of work at the Imperial College of Science, in which $P$, $H$, $T$, measurements are being made in the pressure range 350–1,000 atm. at temperatures up to

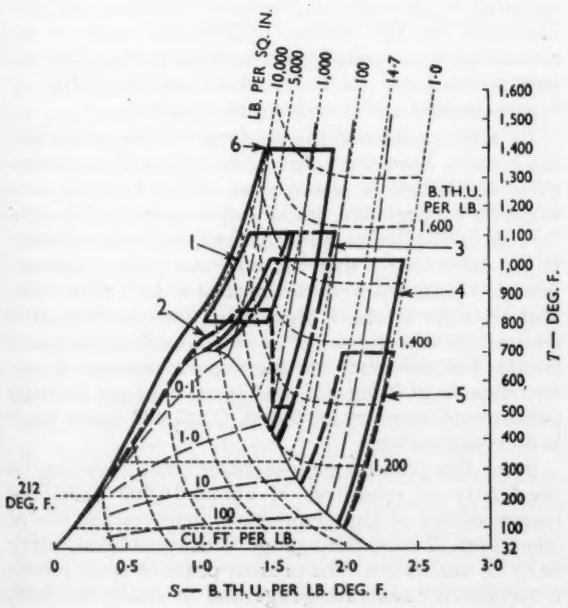



**Figure 2.**

600 deg. C. It is also hoped to obtain data extending to 750 deg. C., but at somewhat lower pressures. The method that is being employed is one used in the earlier work of Callendar and Egerton (1935), in which an electrically-heated flash-boiler produces steam whose temperature and pressure are measured before exhausting adiabatically into a calorimeter-condenser. Improvements in materials of construction and in the techniques of temperature and pressure measurement will, it is hoped, enable the projected upper limits to be achieved without undue difficulty. In the construction of the new plant, Nimonic 80 has been extensively used. This is a nickel-chromium alloy containing titanium and aluminum, which possesses exceptionally good creep properties at high temperatures. At 600 deg. C., for example, under a stress of 25 tons per sq. in., the extension of a cylinder 0.276 inch in diameter and 3 inches long was found to be less than 0.1 per cent in 500 hours.

The boiler contains 100 feet of Nimonic tubing of inside diameter 3/16 inch and outside diameter 9/16 inch in twelve passes, the tubes being heated by an alternating current passed through the walls. From the boiler, the steam flows into a superheater, which is independently heated by the same method, and thence into a pocket where the pressure and temperature are measured. The steam then expands adiabatically through a small orifice into a condenser, and the rate of flow and temperature of both the condensate and the cooling water are measured. The pressure in the plant is controlled by varying the output of the boiler feed-pump or by changing the size of orifice, and the temperature by varying the output of the boiler and superheater transformers. Temperatures are measured by platinum resistance thermometers and pressures by a free-piston pressure balance.

### THE MEASUREMENT OF HIGH PRESSURES

High pressures are most conveniently measured by some form of secondary gauge, the operative element of which should have a quick response and be of a form which can be accommodated in the experimental apparatus. Such a gauge requires calibration over its full range against a primary gauge which measures pressure in terms of fundamental units, or by reference to two or more fixed pressure points, which have in turn been established by means of a primary gauge. In work extending beyond 10,000 bars, the gauge most commonly employed is one depending on the measurement of the change of electrical resistance with pressure, of a metal wire. The alloy manganin is particularly suitable for this duty, since its resistance has a low temperature coefficient at room temperature and changes almost linearly with pressure. Up to 25,000 bars, the change in resistance with pressure can be expressed as an equation of the second degree, the deviation from linearity being about 2 per cent.

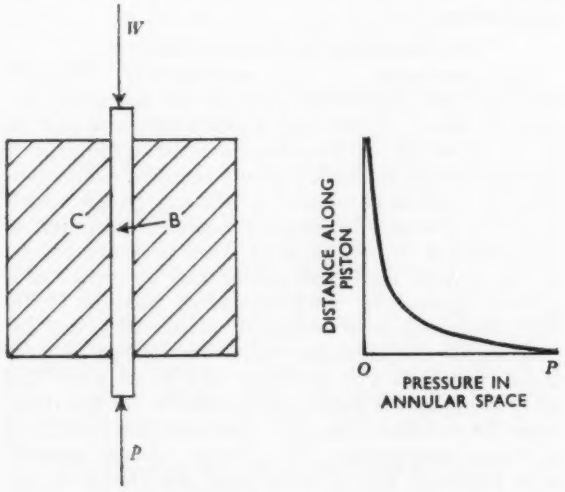
Primary gauges take the form either of a balanced free piston of known cross-sectional area or of a mercury column of reduced height. In both cases, the pressure to be measured has to be contained within

a cylinder which forms part of the gauge, and which must be sufficiently strong to withstand the resultant stresses without permanent deformation. This condition sets an upper limit to their readings, which, with the materials of construction at present available, is about 12,000 bars.

The operation of the free-piston gauge may be understood by reference to Fig. 3, which shows in section the piston-cylinder assembly. The pressure $P$ to be measured is transmitted by means of some suitable liquid to the underside of the piston B which is free to move in the cylinder C but is restrained by a counterbalancing weight $W$ supported at its upper end. If the weight of the piston is $w$, and its cross-sectional area $A$, and $p$ is the atmospheric pressure, then under ideal conditions, when the piston is in equilibrium

$$P = \frac{(W + w)}{A} g + p$$

The assumptions implied in this relationship are that the piston is truly cylindrical and free to move in the cylinder with friction, that no distortion of the piston or cylinder takes place and that there is no measurable leak of liquid past the cylinder. None of these assumptions is valid over a wide pressure range. In particular, the leakage past the piston is a function of pressure, and results in a lifting force on the piston owing to viscous drag, which is equivalent to an increase in the effective area of the piston. If the dimensions of the assembly remain unchanged under load, it can be shown that the effective area may be taken, without serious error, to be the mean of the cross-sectional areas of the piston and cylinder. At high pressures, however, elastic deformation takes place, and it is possible to calculate from elastic theory the effect of distortion on the effective area. In this way, Bridgman estimates that, for his particular gauge, the effect would require a correction of about 1 part in 500 at 10,000 bars (Bridgman 1949).




B Piston.
C Cylinder.
$P$ Pressure in annular space.
$p$ Atmospheric pressure.
$W$ Counterbalancing weight.

**Figure 3. Section of Piston Assembly.**

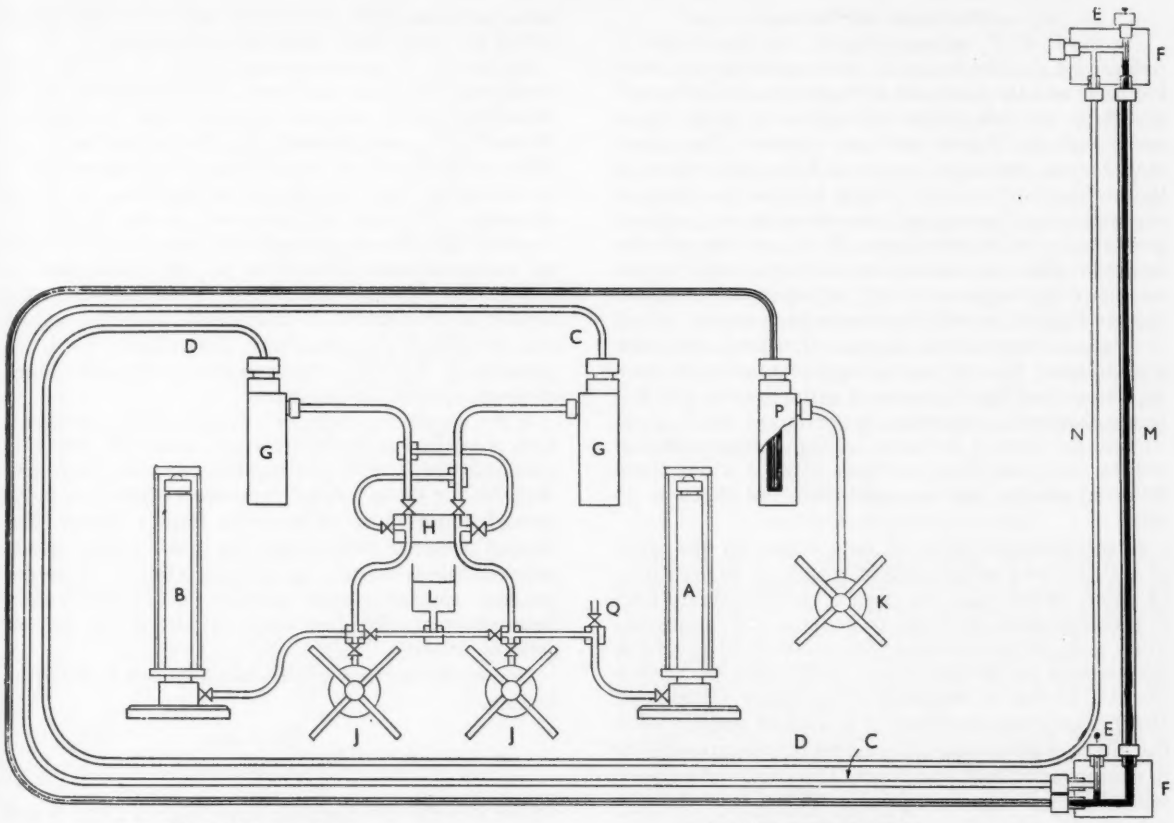
It is, therefore, necessary to modify equation (1) to the extent of replacing $A$ by $(A_e)$, the effective area of the piston at pressure $P$. The value of $(A_e)$ cannot be calculated directly from the dimensions of the piston and cylinder, but may be obtained by calibrating the gauge against a column of mercury of reduced height. We have recently constructed and erected such a column at the Imperial College, and have shown how to estimate the various corrections required to its readings (Bett, Hayes, and Newitt, 1954).

A diagrammatic layout of the column and ancillary equipment is shown in Fig. 4. The column consists of an inverted U-tube, one limb M of which is filled with mercury and the other, N, with liquid paraffin. The mercury limb consists of a stainless-steel tube 30 feet long, connected at each end to a steel block F, into which electrical contacts are screwed. These contacts with a suitable signalling device, serve to locate the mercury-oil interfaces. The two columns are contained in a water-jacket, the temperature of which is maintained constant to $\pm 0.02$ deg. C. The pressure at the upper and lower end of the column is transmitted to one or other of two free-piston gauges A and B. Each gauge is provided with a screw ram injector J, by means of which the pressure may be adjusted to fine limits.

In operating the column, the gauges A and B are connected alternately to the top and bottom of the column, and pressure is built up by increments represented by the indicated height of mercury suitably corrected for the several hydrostatic heads in the connections. In applying corrections to the observed height, accurate data for the compressibility of liquid paraffin and mercury are required.

By a comparison of the readings of free-piston balance and a mercury column, it is possible to determine the effective piston area of the balance as a function of pressure, including corrections for distortion, lack of symmetry, leakage, and other causes. It has been found that the effective piston areas of pressure balances sometimes show a drift with time, and, in order to check them from time to time, it is convenient to make use of one or more fixed pressure points. For this purpose, the vapor pressure of carbon dioxide at 0 deg. C. (34.8 bars) and the freezing pressure of mercury at 0 deg. C. (7,490 bars) have been recommended.

Since the primary gauges described above can be used only to pressures of about 10,000 bars, the measurement of higher pressure involves the use of some form of secondary gauge with some uncertainty as to its calibration. The present practice is to employ a manganin resistance-gauge and to check its readings against one or more fixed pressure points, which




A, B Free-piston gauges.
C, D Pipe lines filled with paraffin.
E Insulated plug.
F Block for electrical contacts.
G Mercury trap.
H Manifold.
J Screw-ram injector.
K Small injector.
L Oil reservoir.
M Limb of U-tube filled with mercury.
N Limb of U-tube filled with paraffin.
P Mercury trap.

**Figure 4. Diagrammatic Layout of Mercury Column for Measurement of High Pressures.**

have been established by other means. The only point which is at present available beyond the range of a primary gauge is the I-II transition pressure of bismuth (24,930 bars) which has been measured by Bridgman (1949), using the method of volume discontinuity. By this method, pressure is transmitted directly to a specimen of the metal contained in a cylinder by means of a closely fitting piston and the change in volume with pressure is measured by the movement of the piston. Errors will arise due to frictional effects and distortions of piston and cylinder; and the precision of the final measurement will depend upon the accuracy with which these errors can be determined. Bridgman was able to measure directly the distortion of the cylinder at the piston face, by means of an electrical internal gauge, and to minimize frictional effects by reducing the thickness of the piston packing rings. It is difficult to estimate the absolute accuracy of the final transition pressure, but the total frictional effect obtained by allowing the transition to take place for both increasing and decreasing pressures was about 6 per cent. Making use of the mercury freezing and the bismuth transition pressures, Bridgman found that the change in resistance with pressure of a manganin wire could be expressed as an equation of the second degree, the departure from linearity being of the order of 2 per cent at 25,000 bars.

Beyond 25,000 bars, there is no method available for determining pressure, other than that of an extrapolation of the pressure coefficient of some measurable property of the solid state or a direct measurement of the force acting on the specimen. At such pressures, stress differences in compressed solids, of the order of their plastic shearing strength, are to be expected. The shearing strength increases with pressure in a way characteristic of the substance; for organic compounds, for example, it may rise exponentially. In the case of certain metals, such as tin and iridium, however, the shearing stress is only a few thousand lb. per sq. in., even at high pressures, and, if a sample under compression is thin enough, stresses sufficiently close to hydrostatic conditions for purposes of pressure measurement may be realized.

### THE LIQUID SURFACE

On the $P$, $V$, $T$, surface (Fig. 1), the liquid state is defined by an area bounded by the melting and bubble lines and the isotherm through the critical point, and there are two additional regions in which liquid and solid and liquid and gas coexist. The upper boundary of the liquid region and the upper limit of the melting curve are at present beyond the range of experimental observation, nor does theory indicate how they should terminate. It is not improbable, however, that the distinction between solid, liquid, and gas will disappear at very high pressure and that the melting curve will terminate at a critical point. A single substance will, in general, exist in only one liquid phase, but an interesting exception is helium, which has two liquid phases of equal density but different transport properties. A portion of the $P$, $V$, $T$, surface for helium is shown in Fig. 5, from which it will be seen that there is a triple point at which three different phases are in equilibrium but there is no solid.

A considerable body of data exists on the compressibility of a wide range of liquids up to pressures of about 30,000 bars but over a comparatively narrow temperature interval. In general, the compressibility is found to decrease with increase of pressure, the average compressibility at 12,000 bars being only about 1/15 that at atmospheric pressure (Bridgman 1949). Furthermore, there is a marked tendency for the effect of structural differences on compressibility to disappear at high pressures. Thus, the values for a wide range of organic liquids at 12,000 bars vary by a factor of only 1.8, and the change of relative volumes between 5,000 and 50,000 bars is in the range 0.20–0.25, even when freezing is included.

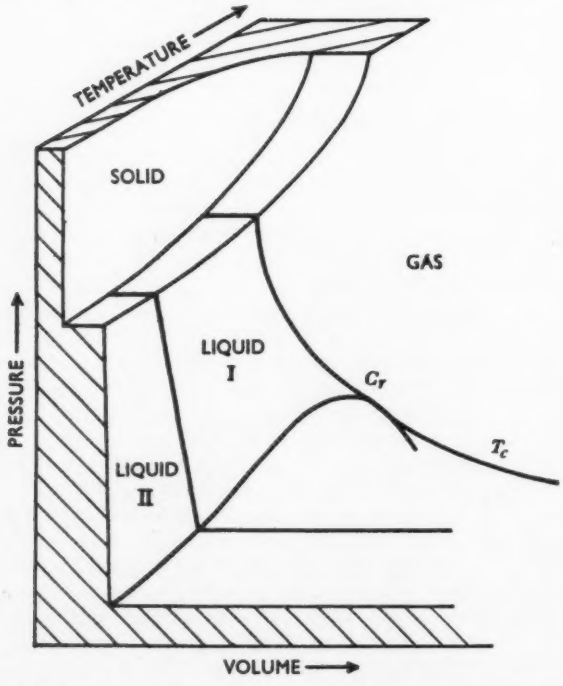



**Figure 5. Pressure, Volume, Temperature Surface for Helium.**

Equations of state representing the $P$, $V$, $T$, relationships may take the form of convergent series equations, which require several virial coefficients related in a complicated way to molecular force fields; or they may be based upon statistical mechanics, in which case simplifying assumptions as to the structure of groups of molecules in the liquid are required. Equations derived in this way are restricted by computational difficulties to the ideal case of spherically symmetrical force fields. Neither approach is, therefore, of immediate practical value, and empirical equations are accordingly used for correlating experimental data over restricted ranges of temperature and pressure.

If the specific volume of a liquid at any temperature is plotted against pressure, a smooth curve is obtained which, for most liquids, can only be represented over an extended pressure range by a polynomial equation of at least the fourth degree. For limited pressure ranges, say, up to 2,000 bars, quadratic equations containing arbitrary temperature dependent constants will correlate the experimental data satisfactorily, but such equations are not of general validity.

One of the earliest empirical equations is that due to Tait:

$$k = C \log \left( \frac{B + P}{B} \right)$$

where $k$ is the compression at pressure $P$, and $B$ and $C$ are constants, the former being usually a quadratic function and the latter independent of temperature. It may be seen that this equation leads to zero specific volume at a finite high pressure and consequently, although it fits closely compression data for a number of liquids up to 10,000 bars, it cannot be expected to hold at very high pressures.

Of the various empirical equations put forward in recent years, we have found the Hudleston equation to be the most useful for correlating compressibility data over a wide pressure range. The equation is derived from a postulated law of intermolecular force

$$F = \lambda (L_o - L) e^{\theta (Lo - L)}$$

in which $F$ is the force acting on one face of a cube containing unit mass of the liquid, $L$ is the length of the cube side, $L_o$ is the value of $L$ at zero (or unit) pressure, and $\lambda$ and $\theta$ are specific constants. Values of $L$ and $L_o$ can be calculated from a knowledge of the thermal expansion and compression of the liquid. Since $F = L^2P$, it follows that $\log L^2P/L_o - L$ should be a linear function of $L_o - L$; hence, the isotherms on a Hudleston diagram are straight lines.

In Fig. 6 a Hudleston diagram for ethyl alcohol extending up to 45,000 atm. and over a temperature range —100 to +175 deg. C. is given. The diagram is based upon measurements by Amagat, Seitz and Lechner, and Bridgman, and its value for correlating these several sets of data will be immediately apparent.

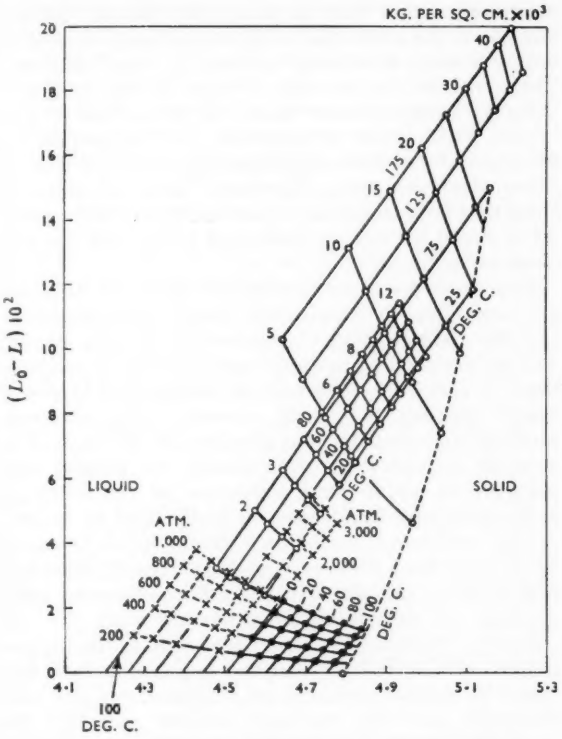



**Figure 6. Hudleston Diagram for Ethyl Alcohol.**

We have found (Bett, Weale, and Newitt 1954) the Hudleston equation represents accurately the $P$, $V$, $T$, relationship of all the liquids to which we have applied it, including water which behaves in an anomalous manner. It also represents the $P$, $V$, $T$, data for solids at pressures up to 100,000 atm., the highest pressure at which measurements have been made; to within the experimental accuracy of the original data.

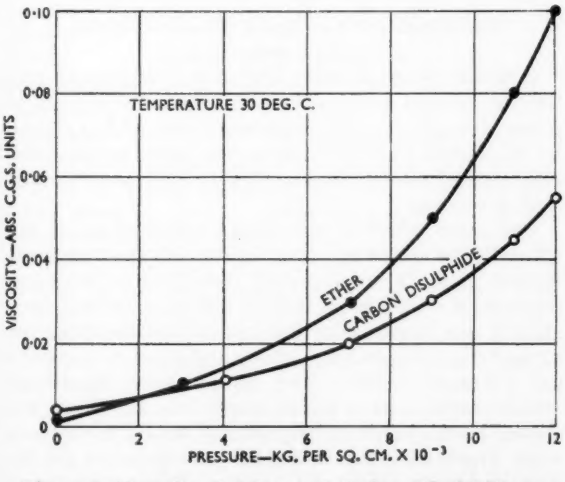



**Figure 7. Viscosity of Ether and Carbon Disulphide as a Function of Pressure.**

### THE CHANGE IN THE VISCOSITY OF LIQUIDS WITH PRESSURE

One of the difficulties encountered in experimenting with liquids at high pressures is due to the very large changes in viscosity with pressure. With the exception of water, the viscosity of all liquids increases with pressure at a rapidly increasing rate, as may be seen from Fig. 7, which is based upon Bridgman's measurements for carbon disulphide and ether at 30 deg. C. (Bridgman 1949). In general, the largest effects are found for substances with the most complicated molecules, it being supposed that viscosity involves a temporary freezing together of the molecules of the liquid into orientated clusters.

In the case of water at 0 to 10 deg. C. there is a minimum viscosity at a pressure of about 1,000 kg. per sq. cm., due probably to a decrease of association at the higher pressures.

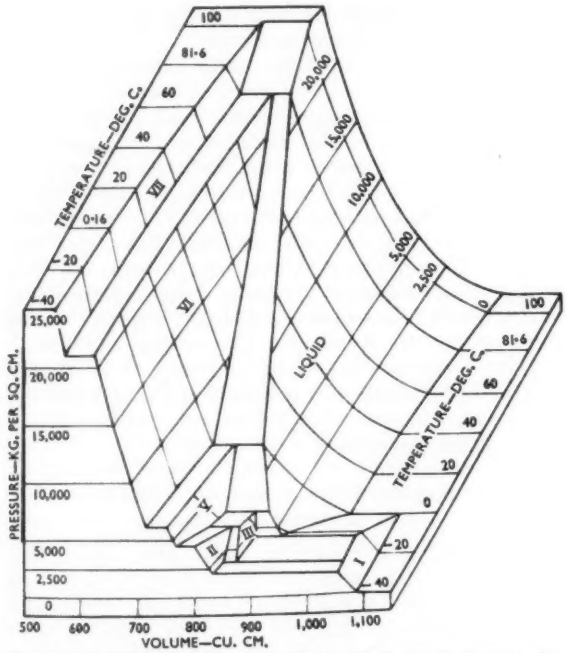
### THE SOLID SURFACE AND THE MELTING AND SUBLIMATION CURVES

The regions of coexisting solid and liquid, and solid and gas phases appear on the $P$, $V$, $T$, surface as narrow shelves, the former extending indefinitely along the pressure axis and the latter terminating at the triple point. The projection of these shelves on a pressure-temperature plane gives the corresponding melting and sublimation curves.

The melting point varies with pressure according to the Clapeyron equation $\triangle V.\, dP = \triangle S.\, dT$ and the melting curve may, therefore, be derived, together with the latent heat of fusion ($T\triangle S$) from $P$, $V$, $T$, measurements only. Up to some 12,000 bars, there is no apparent change in the character of the melting curves of most solids and nothing to indicate that $\triangle V$ and $T\triangle S$ would vanish together. $\triangle V$, in fact, continues to decrease with rising pressure, but at a constantly decelerating rate and, in some cases, there is an increase of $T\triangle S$ sufficiently large to result in an increase of entropy difference between liquid and solid. The large increase in the viscosity of liquids with pressure makes it difficult to explore the upper end of the melting curve to still higher pressure and there is, in consequence, still some doubt as to whether it would eventually reach a maximum critical value, rise to an asymptotic temperature or continue into the region of atomic breakdown.

It is significant that the melting curve may often be followed to temperatures considerably higher than the critical temperature between liquid and vapor (Simon and others 1930), a circumstance which suggests that any gas may be condensed directly into a solid phase at any temperature above the critical by the application of sufficient pressure.

Although in Fig. 1 only a single solid phase is shown, it has been found that, in approximately one-third of all the substances examined up to pressures of about 100,000 bars, polymorphic forms exist which divide the solid surface into a number of stepped areas. This is well illustrated by Fig. 8, which is taken from a $P$, $V$, $T$, surface for ice constructed by Verwiebe from Bridgman's data.




Constructed by Verwiebe on the basis of measurements by Bridgman.

**Figure 8.** *P, V, T,* **Surface for Water Showing all Points.**

The compressibility of the elements is a periodic function of the atomic weight, it being probable that the solid rare gases are the most compressible, with the alkali metals coming next in order. With few exceptions, the coefficient of compressibility decreases with increasing pressure.

The volumes of the five alkali metals as a function of pressure up to 100,000 kg. per sq. cm. at room temperature is shown in Fig. 9 (Bridgman 1949). It will be seen that caesium occupies a unique position, in that it has a compressibility of the order of the most compressible liquids and shows two reversible volume discontinuities at 23,000 and 45,000 kg. per sq. cm., respectively. According to Bridgman, the mechanical characteristics of these discontinuities are indistinguishable from those of polymorphic transitions, and the lower one is almost certainly due to a lattice change from body centered to face centered. The upper one is not easy to account for, since the volume change is more than nine times that of the lower, which itself corresponds to a close-packed structure. It has been suggested that it may be due to some electronic rearrangement; and calculations show that the forcing of an electron from a 6s to a 5d orbit would, in fact, be sufficient to account for the observed contraction.

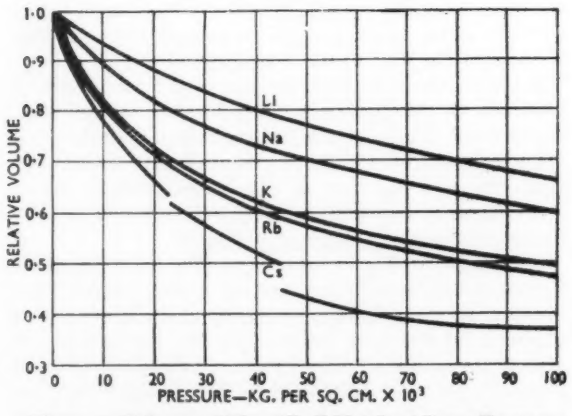



**Figure 9. Volumes of Five Alkali Metals at Room Temperature as a Function of Pressure to 100,000 kg. per sq. cm.**

Even over the moderate range of pressure at present accessible to experiment, there are indications that the distinguishing characteristics of solid, liquid, and gas are tending to disappear; and theory predicts that, at very high pressure, all matter would eventually disintegrate, giving a homogeneous electron phase of high density. It is possible, on the basis of a suitable hypothetical atom model, to predict the pressure at which some indication of the onset of such structural breakdown is likely first to be observed and, in general, this is found to lie between $10^6$ and $10^8$ bars. But, even at pressures between $10^5$ and $10^6$ bars, changes similar to those observed with caesium are most likely for other elements.

It may, therefore, be anticipated that, as the higher regions of the *P, V, T,* surface are approached, the phase boundaries between solid, liquid, and gas will disappear and the resultant surface will first be broken by discontinuities, due to successive changes in the electronic configuration of the atoms, and will finally assume the characteristics of a single highly condensed phase.

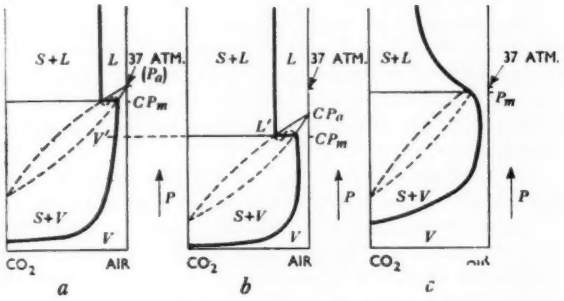
There are many reasons for supposing that matter may exist in far more highly condensed forms than those found on the earth's crust. Thus, pressures of the order of $10^7$ bars, or greater, are postulated for the interiors of the white dwarf stars, and Van Maanen's star, for example, is estimated to have a mean density of over 5 tons per cu. in. It would appear indeed that by far the greater proportion of matter in the universe exists in highly condensed forms.

### PHASE BEHAVIOR OF SOME BINARY SYSTEMS AT HIGH PRESSURES

It would be impossible, within the compass of this lecture, to deal adequately with the many aspects of phase change in multicomponent systems; but it may be of interest to draw attention to some unexpected and unusual effects associated with binary systems at high pressures.

One such effect is sometimes referred to as the solubility of solids in gases. In Fig. 10, the phase relations of the system carbon dioxide-air (the components of which have widely different critical constants) are shown *a* at the critical temperature for air and *c* at temperatures above and *b* below the critical (Webster 1952). The liquid-vapor equilibria, which would exist in the absence of a solid phase, are shown by the elliptical regions defined by the broken lines. The solid-liquid and solid-gas equilibria are indicated by the thickened lines, each of which has a point of inflection at the condensation pressure of the

air-carbon dioxide mixture, the critical pressure of the mixture being slightly below that of air. A comparison of Fig. 10 *a* and *b* suggests the possibility that air saturated at a given temperature would contain more carbon dioxide than air saturated at a higher temperature but at the same pressure. This is contrary to Dalton's law, which states that the molar fraction $x$ of carbon dioxide in equilibrium in the vapor phase at a given temperature should be given by $x = p_s/P$, where $p_s$ is the saturated vapor pressure of carbon dioxide at the temperature in question and $P$ is the total pressure.




*a* $T = -140.7$ deg. C. (critical temperature of air)
*b* $T < -140.7$ deg. C.
*c* $T =$ critical temperature for mixture ($> -140.7$ deg. C.)
$P_a$, $P_m$ Critical pressures of air and mixture.
$CP_a$, $CP_m$ Condensation pressures of air and mixture.

**Figure 10. Phase Relations of the System Carbon Dioxide —Air.**

Recently, Webster has examined this system from atmospheric pressure to 200 atmospheres at temperatures between —110 to —196 deg. C., with results summarized in Table 1.

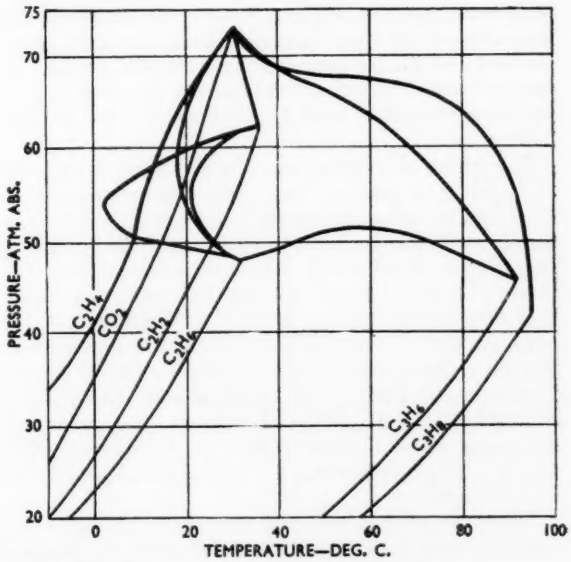
TABLE 1—*(Webster). Deviation of Carbon Dioxide in Air from Dalton's Law*

| Temperature, deg. C. .... | —110 | —121 | —130 | —140 | —145 | —150 |
|---|---|---|---|---|---|---|
| Saturated vapor pressure of carbon dioxide, mm. of mercury .... | 34.63 | 8.57 | 2.31 | 0.431 | 0.168 | 0.060 |
| Total pressure, atm. | Deviation = $P_s/P_a$ | | | | | |
| 10 | 1.19 | 1.25 | 1.50 | 1.50 | 1.5 | 1.4 |
| 20 | 1.55 | 1.55 | 1.61 | 2.02 | 3.0 | 3.4 |
| 30 | 1.92 | 2.28 | 3.61 | 4.8 | 9.4 | 21.3 |
| 40 | 2.6 | 3.4 | 7.0 | 39.5 | 78.0 | 195 |
| 50 | 3.4 | 5.5 | 12.4 | 65.0 | 134 | 275 |
| 60 | 4.9 | 8.2 | 26.3 | 84.0 | 169 | — |
| 70 | 6.7 | 14.0 | 40.0 | 108 | 220 | — |
| 80 | 9.4 | 20.1 | 50.1 | 140 | 245 | 485 |
| 100 | 15.4 | 34.9 | 76.1 | 215 | 327 | 611 |
| 150 | 31.2 | 69.2 | 136 | 370 | 527 | 1,040 |
| 200 | 54.0 | 103.0 | 200 | 542 | 775 | 1,481 |

It will be seen that the apparent vapor pressure of carbon dioxide is increased when the solid is in contact with a compressed gas, the value at —150 deg. C. being more than 1,000 times its normal value in the presence of air at 200 atmospheres. This excess solubility of a solid in the gas phase is a perfectly general phenomenon, and may be expressed quantitatively in terms of a virial expansion in which the successive coefficients represent the clustering of single gas molecules, pairs of gas molecules, etc., around one molecule of solute (Ewald and others 1953). Its importance lies in its application to processes for the separation as solid phase of vapor impurities in industrial gases and for the fractional sublimation of mixed solids.

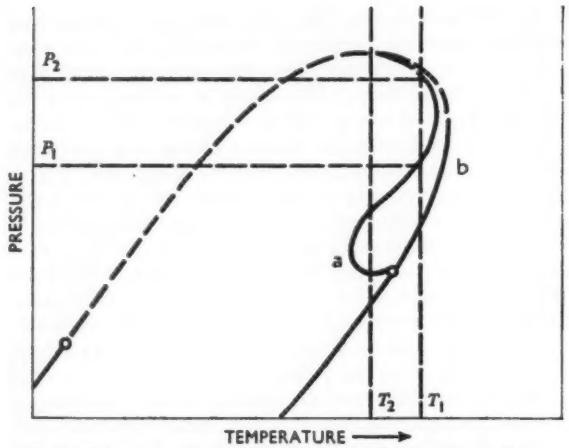
A somewhat similar phenomenon sometimes termed gas-gas equilibrium, or limited mutual solubility of gases, has been noted in the liquid and gaseous phases of certain binary systems, the components of which have widely differing critical temperatures. It will be recalled that, in the case of pairs of substances whose critical temperatures are not too far apart, the curve connecting the critical temperatures and pressures of all mixtures of the two (the plait-point curve) may take any one of the forms shown in Fig. 11, the curve in no instance extending beyond the critical temperature of the least volatile component (Haselden and others 1951).

When the critical temperatures of the components are far removed from one another, other types of curve, such as those shown in Fig. 12, may be obtained having the common feature of extending beyond the critical temperature of the least volatile component (Krichevsky and Bolshakov 1941; Lindroos and Dodge 1952). Plait-point curves of type (a)




$C_2H_4$ Ethylene. $C_2H_6$ Ethane.
$CO_2$ Carbon dioxide. $C_3H_6$ Propylene.
$C_2H_2$ Acetylene. $C_3H_8$ Propane.

**Figure 11. Plait-Point Curves for Mixtures of Hydrocarbons and Carbon Dioxide.**




Critical temperatures of components far removed from each other.

**Figure 12. Pressure Against Temperature Curves.**

have been found for the systems nitrogen-ammonia and nitrogen-sulphur dioxide (Krichevsky and Bolshakov 1941; Lindroos and Dodge 1952) and of type (b) for helium-ammonia and helium-carbon dioxide (Tsiklis 1952). In general, it has only been possible to establish the right-hand arm of the curve, since the least volatile component usually freezes at a temperature well above the critical temperature of the more volatile component.

Referring to curve (a), it will be seen that, at a temperature $T_1$, above the critical temperature of the two components, there are two critical points and two phases which coexist between pressures, $P_1$ and $P_2$. These may be described as two fluid phases of high density or two gas phases. At a somewhat lower temperature, $T_2$, there are three critical points, the lower one being that for ordinary liquid-vapor equilibrium and the upper ones those for gas-gas equilibrium. In the case of systems giving curve (b), gas-gas equilibrium is found only beyond the critical temperatures.

The system nitrogen-ammonia also provides a good example of a curious barotropic phenomenon first observed by Onnes with a helium-hydrogen system at liquid hydrogen temperatures (Onnes 1906). Onnes found that at pressures below 49 atmospheres, the phase richer in helium was the lighter, while above that pressure it was the heavier. The effect was reversible and by varying the pressure it appeared as though a 'gas' bubble sank through a liquid phase. Lindroos and Dodge (1952) found that, below 1,820 atmospheres, all heavy phases of the nitrogen-ammonia system were richer in ammonia, while above 2,100 atmospheres, all light phases were richer in ammonia.

These somewhat unusual effects occurring in binary systems at or near the critical point of one component have been predicted on theoretical grounds, and are due to changes in the relative compressibilities of the two species in a region which the densities of the liquid and vapor phases are of the same order of magnitude.

## SOME PROBLEMS IN THE DESIGN OF HIGH-PRESSURE EQUIPMENT

To conclude this review, some account must be given of the effect on design of large unbalanced stresses on materials used in the construction of pressure apparatus and equipment.

High pressures are conveniently produced by raising the temperature of a working substance at constant volume, as in a steam boiler, by causing the working substance to react chemically in an enclosed space, as in the internal-combustion engine, or by reducing its volume by doing work upon it as in an hydraulic press. The latter method is almost invariably adopted in static experiments in the higher pressure domains. The apparatus employed consists essentially of a piston and cylinder assembly, the piston being forced into the cylinder against the resistance of the working substance by some suitable mechanism.

So long as the metal of which the plant is constructed is not stressed beyond its elastic range in tension or compression, elastic theory enables the stress distribution under load to be estimated with sufficient accuracy to admit of suitable factors of safety being included in the design calculations. In these circumstances, simple and compound cylinders or wire-wound cylinders give satsifactory service. It should be remembered, however, that the walls of compound and wire-wound cylinders are highly stressed under no-load and a limit to their strength is usually given by the maximum initial compressive stress which their core metal is able to sustain.

I have employed both types of construction for cylindrical reaction vessels of from ½- to 1½-inch bore and have had satisfactorily results up to pressures of about 7,000 bars. Several such vessels have been constantly in use for many years without any sign of permanent deformation or fatigue. At various times, attempts have been made to build a compound cylinder to withstand higher working pressures, and one such cylinder, designed for 15,000 bars, is shown in section in Fig. 13*a*. The cylinder is of ½-inch bore, 18 inches long, and is made up of a core over which two outer jackets are shrunk, the internal radii of the jackets being in geometrical progression. The calculated initial stresses due to shrinkage and the resultant stresses under load are shown in Fig. 13*b*. It will be noted that in the bore layers there is an initial compressive hoop stress of 80 tons per sq. in. and a resultant tensile hoop stress of 20 tons per sq. in. (Newitt and others 1937). To withstand these stresses it is necessary to sacrifice ductility and to heat treat the core metal, so as to obtain the highest practicable yield point. This and subsequent cylinders built on the same plan invariably failed at a pressure of about 9,000 bars, a circumferential crack developing in the core just behind the piston head. The reason for this type of failure will be obvious if the change in stress distribution during the period of pressure development is considered. As the piston is forced into the cylinder, the pressure in the reaction space ahead of the piston rises sharply and in the

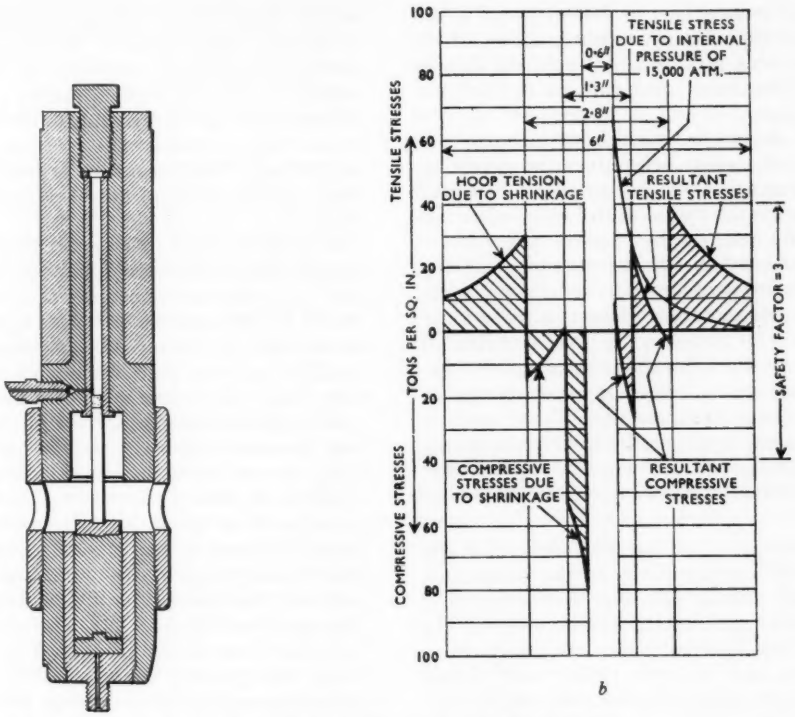



**Figure 13. Compound Cylinder Designed to Withstand aPressure of 15,000 bars.**

space behind the piston head falls abruptly to atmospheric pressure. There is, in consequence, a large stress gradient which builds up immediately behind the piston head as it advances, and failure appears to originate in the narrow band of metal supporting the gradient when the internal pressure reaches approximately two-thirds of the design value. This particular weakness is eliminated in autofrettage construction, the initial stresses in the walls in an autofrettage cylinder due to overstrain being automatically adjusted along the axis to the internal pressure. The conventional theory of autofrettaging is confined to small overstrains (Macrae 1930) and the maximum pressures which can be supported in vessels so designed are far below those required in the higher experimental ranges. In these circumstances, it is necessary to adopt empirical procedures using comparatively large overstrains during autofrettaging and accepting a condition of instability in the resulting vessel. By constant inspection during use, it is usually possible to ascertain when permanent deformations are assuming hazardous proportions and to take the necessary precautions.

Recently, Manning (1945, 1950) has described an approximate method for calculating the radial and hoop stresses in the walls of a cylinder subject to these large overstrains and has shown that no matter how great the bore strain, there will always be a concentric ring in the wall (if it is thick enough) outside which the material is still elastic. This observation affords some justification for a design of compound pressure vessels, in which the inner core is conical in shape and is forced into a retaining jacket by the thrust of the piston as the pressure is developed; by this arrangement, the amount of external support is determined by the internal pressure. The general arrangement of such a vessel is shown diagrammatically in Fig. 14. Employing this type of construction, Bridgman (1940) has experimented with pressures up to 50,000 kg. per sq. cm., with a life for the pressure vessel of from 10 to 20 applications. The princi-

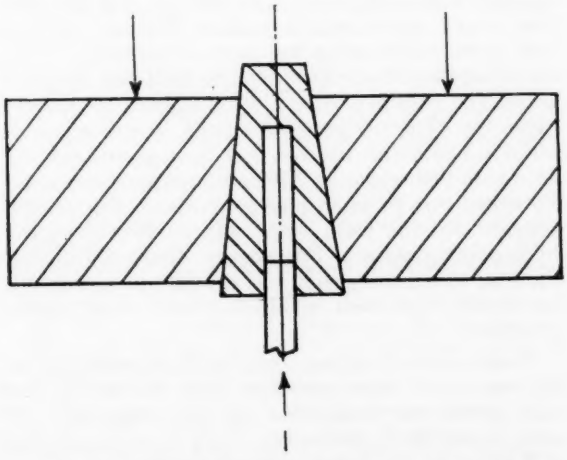


**Figure 14. Compound Pressure Vessel with Conical Inner Core.**

pal defect of this construction is that referred to in connection with compound cylinders, namely, that, as the piston advances, a large stress gradient develops behind the piston head, and rupture is likely to occur in this region.

In principle, it should be possible to increase the strength of a vessel almost indefinitely by adopting a cascade arrangement, in which a number of vessels are placed one inside the other, each being subjected to a predetermined external hydrostatic pressure.

It is usually assumed in the theories of plasticity that pure hydrostatic pressure has no effect on the process of plastic deformation. Since it is commonly accepted that the chief factor in the yield and flow of materials is a function of the shear stresses, this assumption is tantamount to believing, as do designers of high-pressure equipment, that the shear properties of materials are unchanged by hydrostatic pressure. It is, however, well known that hydrostatic pressure may influence the strain-to-failure for materials.

Until a few years ago, the main evidence for the belief that pressure has no effect on the properties of metals at small strains was due to Polanyi and Schmid (1923), who carried out tensile tests on thin wire made from zinc and tin under pressures of up to 40 atmospheres, and to Cook (1934) who determined the shear properties of annealed copper and mild steel under pressures of up to 2,500 atmospheres.

Results obtained by Polanyi and Schmid showed no effect of pressure, but this is not surprising as the pressure range was so small. Cook determined the shear properties under pressure, by subjecting helical springs (10.5 mm. diameter) made from 27 gauge (0.4 mm.) and 19 gauge (1.0 mm.) of mild steel and copper wire to combined axial load and fluid pressure. The coil was suspended from one end of a thick steel tube containing pure glycerine, the load being attached to the lower end of the coil. While hydrostatic pressure was being applied to the glycerine, the tube was laid horizontally, so that no load was applied to the coil; in order to load the coil, the tube was turned into a vertical position. The tests on mild steel were confined to the part of the stress-strain curve between the proportionality limit and the yield point. The results of load plotted against permanent extension, after the removal of load, were very scattered but definitely showed that, for a given load, the permanent extension at 2,500 atmospheres was about 2.5 times that at atmospheric pressure. The results suggest that the yield stress was unaffected by the hydrostatic pressure. For copper, Cook found that the load extension graph was raised, on an average, by about 4 per cent in stress when tested under pressure.

Cook's method suffers from the disadvantages that the test cannot be extended to large strains and that only permanent extensions can be measured. It is also impossible to determine a drop in stress at yield if it exists in the material being tested.

Bridgman (1945, 1952, 1953) has published a considerable amount of work on the effect of pressure on the properties of metals at large strains. His experiments were mainly tensile tests on various grades of steel. One peculiarity of Bridgman's experiments was that he used a plunger to apply the tensile strain to the specimen and, in doing so, the plunger continually increased the hydrostatic pressure during the test. The increase of pressure was quite large, being of the order of 40–80 per cent in most of the tests.

In some of his earlier tests, Bridgman plotted the engineering stress-elongation curves for high-tensile steel at atmospheric pressure and at a pressure of between 20,000 and 30,000 atmospheres. The curves corresponding to the two pressures appear to be roughly parallel, with the curves for the high pressure about 15 per cent higher on the stress axis. In his later experiments, Bridgman felt that it was necessary to make some correction for the fact that the stress across the neck of a tensile specimen was not uniform. A correct allowance was possible only if the problem of the plastic distortion at the neck could be solved. He was able to produce an approximate solution by assuming that the strain across the neck was uniform. Davidenkov and Spiridonova (1946) have also analyzed the problem. The state of stress at the neck has been found to consist of a uniform tensile stress acting along the axis of the specimen, with a superimposed triaxial tension which varies across the section, from zero at the outside surface to a maximum at the center of the specimen. To determine these stresses, it is necessary to know the diameter of the specimen at the neck and the radius of curvature of the neck in a plane containing the axis of the specimen. The practical determination of the parameters, required to analyze the stress, is difficult, especially as the neck frequently becomes very irregular (Bridgman 1945, 1952, 1953).

The results of tension tests in steels, nickel, tantalum, columbium, molybdenum, tungsten, gamma-brass and antimony, under pressure up to 30,000 atmospheres, have shown a very small rise in the stress-strain curves. At low strains, the hydrostatic pressure had no effect on the stress. These results show a fairly considerable scatter, which is not surprising when the difficulties involved in the technique of testing under such high pressures and in interpreting the results because of the complex stress system at the neck of the tensile specimen, are considered.

For ordinary metals, there was one outstanding result of the application of a high hydrostatic pressure, namely, a large increase in the strain-to-failure.

The degree to which ductility is raised by pressure depends on the grade of steel and, in general, is less the harder the steel or the higher the carbon content. A typical example given by Bridgman (1945, 1952, 1953) is that of a 0.45-per-cent-carbon steel, which under atmospheric pressure breaks in tension with an elongation of twofold or threefold; under a pressure of 25,000 atmospheres, an elongation of 300-fold has been observed without fracture.

Bridgman found that the *natural strain* at fracture

is very nearly a linear function of the hydrostatic pressure. This relation holds up to natural strains of 5, that is, up to elongations of 100-fold; at greater strains, individual crystal grains upset the geometry of the necked specimen and measurements cannot be easily made.

The great increase in ductility of steel in tension appears to apply to other kinds of deformation. For example, a punch may be pushed through a sheet of mild steel, if it is immersed in a liquid under high pressure, with no breaking out of the punching or loss of cohesion.

Doubts as to the effect of pressure mainly arise from the results obtained by Ratner (1949), who tested annealed copper, magnesium, beryllium-bronze, two magnesium alloys, a cast aluminum alloy and an aluminum copper-magnesium-zinc alloy in tension under hydrostatic pressure. He used an apparatus capable of producing a pressure of 6,000 atm., although the highest pressure used was 2,200 atm. Except for annealed copper, the stress at a given strain was considerably raised by pressure, 40 per cent in the case of beryllium-bronze at 2,200 atm., the increase being very much higher than that observed by Bridgman on other materials at a corresponding pressure. For copper, the effect of pressure was entirely negligible. Ratner concluded that hydrostatic pressure had a pronounced influence on the whole process of plastic flow, and he thought that this influence depended on the structure of the metal.

All the work reviewed so far has been carried out in tension. In shear, Bridgman (1945, 1952, 1953) has described punching tests under high fluid pressures. With this form of test, it was possible to plot only the shearing stress based on the current area against the penetration, and it was impossible to determine the correct stress and strain because the conditions of plastic flow were not sufficiently well defined. For several steels, the shear stress at a given penetration was considerably raised by pressure, and the penetration required for failure was also increased. At very high pressures, the punch could be driven completely through the steel plate without loss in coherence. It was also observed, in tests on steel subjected to combined torsion and axial compression, that the stress-strain curve was raised, a significant amount by an increase in the compressive force. There is no doubt that these experimental techniques for determining the shear properties are far from ideal, and better results would have been obtained from a straightforward torsion test; but Bridgman considered that the technical difficulties involved in such a test at high pressures could not be readily overcome. Bridgman used the technique of subjecting materials to combined torsion and axial compression to good effect to obtain evidence of polymorphic transitions and to carry out various irreversible effects. For example, red phosphorus may be changed to crystalline black, a transition which is not known to take place under conditions other than shear under a high hydrostatic pressure.

Crossland (1954) has constructed an apparatus in which it is possible to carry out torsion tests under hydrostatic pressures up to 6,000 atm. The shear properties of mild steel, copper, zinc, a silicon-aluminum alloy and a zinc-aluminum alloy (Mazak) were determined in this appartus at pressures up to 3,000 atm., and the results show that pressure has no significant effect on the shape of the stress-strain curves of these metals. The strains-to-failure for all the materials tested, except zinc and Mazak, were considerably raised by pressure. There was some indication that the relation between strain-to-failure and pressure was linear, though these results are not as conclusive as those obtained from tension tests by Bridgman.

The main disadvantage of the torsion test is that the stress is not uniform across the section of the specimen and it is necessary to derive the shear stress against strain curve from a torque-twist record. However, complete records of the shear stress against strain curve at large strains could be obtained without the difficulty experienced in tension owing to the formation of a neck.

Using the cascade principle, Bridgman has succeeded in developing pressures of the order of 100,000 bars, which for various reasons would appear to be about the practicable limit for this type of construction.

It will be seen, therefore, that some major changes in design methods and experimental procedures are required before the higher pressures on which interest is now centered are likely to be achieved.

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# *SOME THINGS MUST BE SECRET*

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*graduated from Kansas State College in Electrical Engineering and Journalism, and worked for 25 years in Kansas, Wisconsin, and Maine as an editor. During this period, he became firmly identified with the viewpoint of the press, and of reporters in general, that facts are public property and should be exposed to the public view. In 1943 he dusted off his EE degree, and joined the Harvard Underwater Sound Laboratory, working on the problem of special torpedoes. For two years he helped scientists, engineers, and Navy torpedomen run experimental torpedoees off the coast of Massachusetts and Florida. When the Ordnance Research Laboratory was organized in 1945 at The Pennsylvania State University to continue the work of HUSL for the Navy, he was made editor. At present he is head of the Reports and Records section of this Laboratory, with the duty of supervising the editing, printing, and distributing all reports issuing from this laboratory, and of receiving, and maintaining security for, all reports received by the Ordnance Research Laboratory from other facilities.*

In this dawn of the Atomic age it is natural that nuclear reaction should have captured the imagination of the public to such an extent that it is erroneously assumed a scientist doing work on special weapons for the national defense must be working on some phase of the atomic problem. It is also a quite natural development that there has been hysterical thinking by persons who have an insufficient background of knowledge to do any constructive thinking on either the potential danger or the best methods of defending ourselves. Unfortunately, it is also true that a few persons who have considerable knowledge have had their moments of being thrown into gibbering hysteria by the sheer magnitude of the forces involved.

The so-called cold war is not only a war of nerves, it is also a technological war. Persons at the policy forming level must be responsible for tactical decisions. In matters of technology, the scientists and engineers are the workers in the ranks who are producing ammunition to carry on this struggle for peace. The technical work must be carried on in secrecy. It probably will be five years after work is started on an important project before the public should hear anything about it. If, during all that time, any information leaks out it may work to our disadvantage. After an idea is developed to a successful conclusion, the persons responsible for deciding on the tactical moves in the cold war may believe that it is to our advantage to keep it in cold storage until a more appropriate time; or they may decide that it is smart to allow it to be announced at once, telling what it is and showing what it will do, but withholding as much information as possible that would be of assistance to the enemy in reproducing this weapon for their own use, or for developing countermeasures that would make the weapon ineffective if used against them.

We must have proper respect for the abilities of enemy scientists, because overconfidence is a weakness which may be fatal. Even though we do not quite believe it we must assume that anything our scientists can originate and develop can be duplicated by enemy scientists. So long as we are able to keep three to five years ahead of the opposition we retain our position of strength. Allowing information to become known which will cut down that lead in time is a fine method of cutting our own throats.

Without being a scientist myself, I have worked intimately with scientists and technical engineers for

more than ten years. It has been very interesting to see how their minds work, to discover that they are just people, and rather frightening to realize that the future of 160 million persons in the United States hinges on the work they are doing under the blanket of secrecy.

This cloak of secrecy, though necessary, is often stifling to the scientist, misunderstood by the public, resented by the press, and played upon by political demagogs. It is true of course that the secret stamp has been used by persons unworthy of the trust placed in them to cover up inefficiency or worse, but these instances are comparatively few and the remedy is to get rid of the dishonest individual rather than eliminate a necessary part of the system. You try to maintain the safety of money in a bank by continually searching for dishonest cashiers rather than by making a rule that no cashier shall be allowed to put his hands on money.

When the wraps are removed from a new weapon to the intense interest of the general public, it must be because the persons we have saddled with the responsibility for winning peace for us have decided this is a wise move in the game of chess they are playing. The scientist who does not follow all of the security rules and regulations no matter how hampering, irritating, or even stupid they may seem to be under certain situations is getting only what he deserves when the roof falls on him. The reporter who uses a keen nose for news and clever powers of deduction to write and print a powerful story that logically leads up to some facts that should not be mentioned, is doing his country and therefore his readers a disservice. This has happened to the chagrin and horror of conscientious individuals who did not duck to the other side of the street when they saw a reporter friend coming. A reporter who has been investigated or threatened with investigation by persons concerned with maintaining security because of stories he has printed, has nothing to point to with pride. The investigators may be mistaken or stupid or have ulterior motives, but if the reporter has this experience several times it certainly looks as though he made a practice of skating on thin ice without a proper regard for the best interests of the people of these United States.

An immense flood of words has been printed about the A-bomb and the H-bomb. Most of the words are written from a basis of ignorance, ignorance as great as my own and I claim no knowledge except what I read in the papers. Of course, this subject hit the front pages with the first bang and stayed there. You can't keep that kind of a cat in a bag. This probably has done but little harm and doubtless has done some good. While we were in the position of having a monopoly of this weapon, it was a strong deterrent against crowding us into a war in which we would make use of it. Information has been released steadily about our buildup in this field that still leaves us in a position of strength. Now you see speculation about a time in the future when the enemy will have enough fire power to destroy us one hundred per cent, and we will have power to destroy them two or three hundred per cent. Obviously it is just as tough to be killed once as it is to be killed two or three times. Knowing something about scientists, the way they work under strict security regulations and the length of time it takes for important projects to be brought to a successful conclusion, I don't believe we of the general public have anything like the full picture. We can know only such parts of the results of the last few years of work as the authorities have been willing to announce to our enemies as well as to us.

When any new weapon is developed that is of sufficient importance to make necessary a complete reevaluation of tactics for offense or defense, there always are self-appointed leaders of thought who are ready to go into a panic.

The bow and arrow was first viewed as a world-toppling development that placed persons of good will at the mercy of aggressors because there was no effective protection against someone who could stand at a perfectly safe distance and shoot his darts with deadly accuracy to the hearts of his victims. The cross-bow was the H-bomb of its day. The prophets shuddered at the irresistible fire power that was made available when bow-men could flop down on their backs and use their leg muscles to give the deadly arrows additional speed and fantastic range.

Battering-rams fixed it so that no place was safe, even behind well built walls, and really, there was little to look forward to but chaos.

Despite the dire predictions of persons who were well informed in then-known methods of defense there always has been a development of effective countermeasures against new measures of offense.

The world is full of persons, of varying degrees of good sense and knowledge of the subject, who are shouting that there is no protection from the H-bomb except mass evacuation. They should add, "this condition is or was temporary." The persons who know only what they read in the papers seem to be more excited by the inevitability of total destruction than the persons who are in position to know the exact present score. Those of us who are in ignorance of work in progress on this problem should not forget that at one time it was quite truly said of the arrow, or the bullet, that the only protection was to run like hell.

The conception of any new weapon starts intensive work immediately on countermeasures. There are two reasons why this is considered of vital importance and must be done at the highest level of our ability and without delay. First, we need to know how best to protect ourselves if the weapon ever should be turned against us; and, second, we need to know all the ways in which the weapon itself may be vulnerable to countermeasures, so that it may be improved to resist such distractions. Following work on countermeasures is work on anticountermeasures and then come counteranticountermeasures; in fact, it is like the ditty about the dog with fleas, the fleas being infested with littler fleas and so on ad infinitum.

If we have a few scientists who can think rings around the men doing the scientific thinking for the opposition, that is good. Much of the work, however, is done by men who know they are not genuises, but who laboriously and persistently turn up one new fact after another. Every so often, one of these new facts proves to be the missing link in some chain of thought that has been driving some top level man to distraction because in the light of all known facts everything will not quite add up. There are lots of apparently brilliant ideas that have only one thing wrong with them: they will not work. Often one little insignificant fact added to what you've got makes not just a little bit more, but all the difference in the world in making a big idea work.

This drives home the need for secrecy covering the day-to-day work of our men in this whole field of endeavor. One little fact that seems to be of quite minor importance may be just the thing that is needed by an enemy scientist to make a big idea of his jell.

In the case of research and development work done for the armed services in the field of special weapons it is not desirable to have total secrecy. Suppose a new and effective weapon of great importance is developed, tested, and manufactured without any potential enemy having found anything about what it is, what it will do, or how it works. Such a weapon can do us no good unless we come to a shooting war, providing full secrecy is maintained. If the enemy is allowed to know enough about this weapon to help deter him from aggressive acts, and not enough to help him in producing such a weapon of his own or developing effective countermeasures against the weapon we have produced, we find this new weapon of immediate value in helping to keep us out of war.

How much to tell is a very delicate problem, which requires the best of judgment and an intimate knowledge of the status of the work being done on a variety of projects, as well as a knowledge of plans at the executive level. These are decisions that should be made at a high level of responsibility. No scientist or engineer working on a problem has permission to use his own judgment in releasing information that he believes to be unclassified. If a reporter corners a scientist friend and starts asking what he believes to be innocent questions he may be placing his friend in a very awkward spot. Smart reporters have been known to make what they thought were wild guesses and have come so close to some well guarded truth that a poor scientist can protest his innocence until he is blue in the face without convincing persons in authority that he is not guilty of an indiscretion.

The person faced with the problem of placing a classification on any bit of writing on a classfied subject must consider many angles. There must be as free a flow of the information as possible to persons who have a need to know, but at the same time, the flow of this information must be restricted as nearly as possible to those who do need to have it. Much more hampering rules are applied to the handling of Secret Documents than to those which are marked Confidential. A Top Secret classification is applied to a document only when its distribution can be confined to a comparatively few persons without seriously impairing its usefulness, unless the information is such that irreparable injury would result if it were made public.

In facilities with which I am familiar only a few individuals are given clearance to see Top Secret material. This does not mean that other individuals are considered to be less trustworthy. It does mean that as a matter of policy the number of persons who have access to Top Secret information is kept at as low a figure as is consistent with a proper handling of the work.

The person who overclassifies a document finds himself subject to criticism just as quickly as if he had underclassified it. But the criticism carries a lot more bite if he has sent something out as Confidential when it should have been Secret than if the reverse were true. He has also immediately let himself in for a lot of extra work because it is his immediate duty to see that the classification is changed to what it should be on every copy of the report which has been distributed. The result, of course, is that if one has doubt as to what the classification should be, he leans toward the higher classification, so as to be safe from a security standpoint. The inexperienced person is more likely to overclassify than is the person of more mature experience.

The fact that a person is cleared for Secret or Top Secret information does not at all mean that he can easily obtain copies of all Secret or Top Secret information. A secret is really a secret only so long as it is told to no one. It is good theory to consider that the fewer persons there are aware of certain facts, the less likelihood there is these facts may somehow become known to subversive individuals. Therefore, in all areas of critical information the theory is followed that the information should be made available as freely as possible to persons who should have it in order to increase their efficiency in the work they are doing but that the total number of such individuals should be kept to a minimum. A scientist who is working on Top Secret material in one line of endeavor and whose integrity is unquestioned by everyone would find it quite difficult to get permission to look at Confidential material in some other field of endeavor which could serve the purpose only of satisfying his natural curiosity. The properly cleared individual who can establish his "need to know" with the proper authorities is supposed to experience no difficulty at all in getting what he may want.

Of course, when you lay down a lot of rules under which everyone concerned must operate, you have what is popularly spoken of as "red tape." The rules governing all phases of the handling of classified written material are many and rigid. It is a field of endeavor that is all bound around with red tape. This seems to be necessary; in fact, it seems to be the only way in which it can be handled adequately. It does lead to many situations which are irritating to the

persons involved. Certainly the scientist who needs to know certain facts in order to do his job efficiently is bound to feel frustrated by the red tape which prevents his getting immediately the help which would be of such value to him. The person who cuts through this red tape should, and does, find himself in trouble, but every organization doing any large amount of work with classified information needs to have someone in the organization whose responsibility it is to keep this red tape untangled. Most scientists of experience are willing and glad to work with these individuals who, by virtue of learning all the complicated rules involved, are able to see that reasonably good service is maintained. The young and impatient scientist is the one who finds it hardest to live happily with this situation.

After all is said and done, it is easier for the person with a scientific mind to put up with this sort of frustration than for a business man to do so. The scientist has trained himself to view things objectively. If you can give him good logical reasons to prove the rules are really necessary, he will accept them, because he has trained himself always to accept something that is proved to be true, even though he does not like it.

Scientists do their work on the frontier of knowledge. Any information explained and discussed in textbooks or in technical journals is knowledge they consider anyone can have by going to the trouble to look it up. To the man working on the outer fringe of knowledge whose prime purpose in life is to discover, understand and prove facts that no one has previously either known or understood, the discoveries of other persons working on this frontier are of vital interest. To the scientist, a free flow of all this new knowledge is the only completely satisfactory arrangement. Any rules of secrecy are an evil, therefore, from the scientific viewpoint, but the good scientist accepts as fact that it is a necessary evil.

In the field of special weapons a complete freedom of exchange of ideas cannot prevail because it is a highly competitive field and the public interest demands that we keep two or three jumps ahead of the enemy who is also working along the same lines. The argument is sometimes made that the public has a right to know what is being accomplished in this field with public money. This argument is one hundred per cent false at the working level but is perfectly valid providing the information is obtained with the approval of persons in positions of top responsibility in policy forming.

If the Army, the Navy, the Air Force, the Secretary of Defense, and the President decide that the time has come when it is wise for certain information to be made public, it is a considered decision made after weighing the advantages against the disadvantages. The decision is made with the full understanding that information given to the public is information given to the enemy.

When a dramatic announcement is made of a special weapon, with pictures showing it in action—a weapon which can see, hear, smell or taste, and then instantly and automatically act on the information it obtains to dart at high speed to the target and destroy it—the announcement is made because someone in position to accept the responsibility has decided after weighing the arguments, pro and con, that the time has come when it is wise to tell this. Now a gadget like this does not happen overnight. There is no doubt that engineers were working on this device in complete secrecy five years ago. The information and the ideas they were developing at that time would have made intensely interesting reading, especially to the enemy. Leaks at that time probably would have set the enemy ahead several years because you may be sure the enemy is working like mad on just as fantastic weapons as we are. It will only be a matter of time until they come out with a loud "me too." There also is no doubt that at the time of announcing one weapon, which instantly captures the public's fancy as being the last word in fantastic accomplishment, scientists are busily working in their secret cells at ideas that will make this device obsolete. When the "me too" does come from the opposition it will not matter too much. If we have confidence that our scientists can keep two jumps ahead in this rat-race we can face the situation with optimism. They are always working on ideas that will be very much hush-hush for five years.

The idea is to keep out of trouble by virtue of always being in a position of strength. When we complete a device that can be used with telling effect in any phase of defense it is without any wish that it shall ever be necessary or desirable to use it in anger. The thought is rather that its existence will make aggressors gnash their teeth and postpone any serious plans for aggression to a more propitious moment.

There are several reasons why we should have a great deal of confidence in our scientists and in their ability to keep ahead of scientists working for our enemies. In the first place, a democracy gives a better climate for scientific work than is true in a dictatorship. A scientist is working at a great disadvantage if he does not approach his work in a purely objective manner. If he finds himself in the position of trying to avoid getting certain answers because he knows such answers would make some person in a position of great power angry, he is lost, because by adding a little here and subtracting a little there, he always can come up with an answer that will keep him out of trouble. What he must do is to let the chips fall where they may and be able to say, this is the truth, take it and like it or just take it. If a man happens to be working where an unpopular answer will get him into disgrace, it too often will happen that the obtaining of such an answer will be avoided at the expense of overall knowledge.

Another reason why we should have confidence in the future of our own research is that our young and more obscure scientists are brash enough to question in their own minds the statements and findings of the men who have quite exalted reputations in their field. Before World War II the German scientist held an enviable reputation. This reputation was well earned,

well deserved and had been held for a great many years. One weakness that he had, however, was to believe that if a German scientist of sufficiently high reputation said a certain thing was true or was not true, that put a period to that matter. No budding German scientist would think of questioning what the big man said had been proved. I recall one example taken from World War II which shows how this trait worked out to the great disadvantage of the Germans and to our advantage. From the beginning of World War II the submarine was recognized as a real menace. It succeeded in doing tremendous damage. All of the submarines of that day were slow and they were quite vulnerable to depth charges set off in the right place. There was, however, a great deal of ocean in which the submarines could hide and they were succeeding in doing it quite effectively. A great many things were done to try to minimize this menace, and one of the projects was the development of a special torpedo that had the ability to track down the submarine that was moving away at slow speed and destroy or cripple it. Losses due to submarines were still at a very high level when this new torpedo was ready to put into action. The British gave it as their opinion that we would have not more than three weeks to make use of the torpedo effectively after the first one was fired until the Germans would have a countermeasure which would make it ineffective. Our people accepted this opinion as being probably true because unfortunately it was rather a simple matter to devise a countermeasure that would so attract the torpedo that it would surely ignore the real target. To the amazement of everyone, after this torpedo had been in use for eighteen months it still seemed that the Germans did not know what it was or how it worked. After the war was over, we found out the inside story as to why this was true. The Germans had earlier worked on a similar torpedo and had proved to their own satisfaction that a torpedo of that size using those frequencies was impossible. They knew so thoroughly that what we had must be something else that when one of their spies actually sent them some quite accurate information, they knocked his ears down by telling him to quit reading American illustrated stories and send them something they could use.

Face the future with confidence. We have what it takes in brains and judgment at the top, and technical ability and even genius in the field of research and development. Let the boss be the boss, and let's not kill any goose that can lay golden eggs if it can be avoided.

# *A REVIEW OF SHIP VIBRATION PROBLEMS*

**ACKNOWLEDGEMENT**

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## PART I — INTRODUCTION

PUBLICATION of concise reviews of past achievements is one of the valuable duties undertaken by industrial research organizations. They provide a fund of experience whereby former troubles may be avoided, and they sometimes contain the seeds of knowledge from which may grow ideas and inventions to stimulate further progress. Papers dealing with particular fields of inquiry, by individual members of a research organization, are always welcome, especially when they are presented without excessive use of specialized terminology. The recent paper[1] on ship and machinery vibration problems by Mr. T. W. Bunyan of the Engineering Research Department of Lloyd's Register of Shipping is an excellent example of these individual contributions based, as it is, upon a wide and authoritative experience.

As Mr. Bunyan himself remarks at the beginning of his paper, the Research Department of Lloyd's Register of Shipping enjoys the privilege of dealing with about 150 investigations annually, covering a world-wide field. Many problems are common to a large number of vessels, wherever built or engined, and of these, vibration problems relating to hulls and machinery predominate.

The paper evoked an interesting and informative discussion which ranged over practically every aspect of the subject, and it was evident that the trend towards large highly-powered single-screw cargo ships and tankers with machinery delivering powers in the region of 20,000 s.h.p. to a single propeller [2, 3] was presenting the industry with a number of troublesome vibration problems, particularly in vessels with machinery aft.

### PROPELLER EXCITED VIBRATION

The principal factors contributing to this situation are increased propeller excitations due to greater concentration of power in a single screw, and increased size of single-screw vessels which tends to bring criticals corresponding to the higher modes of hull vibration into the service speed range. Since the propeller is ideally situated for exciting all the principal modes of hull vibration it is evident that ability to concentrate large powers in a single screw depends to a considerable extent upon success in applying methods for maintaining propeller excitations within permissible limits. In this connection it should be borne in mind that severe local vibration, particularly in the stern of the ship, can be excited by the propeller even though there is no hull critical at or near the service speed, because the propeller is situated where it can excite all the principal modes simultaneously and the total amplitude thus accumulated may be quite severe even though none of the modes is resonant at the operating speed.

It was therefore not surprising to find a substantial part of Mr. Bunyan's recent paper [1] devoted to consideration of propeller-excited vibration; nor to learn that this problem is being attacked vigorously both analytically and experimentally. A fundamental requirement is the smoothest possible flow of water through the propeller and this involves questions of after-body design, propeller aperture clearances, and the design of the propeller itself, all considered with due regard to maintaining the highest possible propulsive efficiency. A great deal has been accomplished already and phrases such as "wake-adapted" screws and "clear water" rudders are beginning to find their way into the literature. Much more remains to be done, however, before the problem can be handled with reasonable assurance in the design stage; in the meantime, as Bunyan's paper clearly demonstrates, the experience already gained has proved of immense assistance when trouble was encountered in an existing vessel.

The first systematic studies of ship vibration were undertaken in the latter part of the nineteenth century. From 1884 to 1900 many notable papers were presented by the leading specialists of the day, at the meetings of the Institution of Naval Architects, and others appeared in the Technical Press.

As early as 1893 Otto Schlick contributed a paper [4]

describing the Pallograph, which was probably the first scientifically-designed instrument to be used for measuring and recording ship vibration. Among other applications it was used for measuring vibration during the trials of the *Lusitania* in 1907.

### LARGE RECIPROCATORS

The period from 1884 to 1900 was the hey-day of the reciprocating steam engine. With cylinder diameters up to 9 feet and strokes up to 6 feet, these structures were the engineering masterpieces of the nineteenth century. Their massive reciprocating and rotating assemblies introduced serious problems of engine balance and it is not surprising to find that in this early work on ship vibration the engine was regarded as the principal source of disturbance.

The theory of engine balancing was worked out in great detail, not only with regard to primary and secondary forces and couples, but including higher order disturbances as well. Practical methods of dealing with the problem were developed, of which the Yarrow-Schlick-Tweedy system of engine balancing, introduced about 1894, was an outstanding example.

The propeller does not appear as a very serious source of ship vibration, though there were references to the possibility of excitations at propeller blade frequency and multiples thereof, attributed to the variable nature of the water-flow past the propeller.

The theory of hull vibration, regarding the hull as a freely supported elastic beam, was also well understood. Semi-empirical formulae for calculating the natural frequencies and vibrating forms of the lower modes were published by the French naval architect Normand in 1892 and by Otto Schlick in 1894.[5]

These calculations were not very reliable, however, due to the complexity of the problem and lack of accurate physical data. One can sympathize with the contemporary writer who remarked that while it might be possible to prevent one kind of vibration from becoming unduly prominent, how are we to deal simultaneously with different periodic forces and various modes of vibration of the ship. But appreciation of the seriousness and difficulty of the problem was not widely spread. A correspondent to the technical press in 1897 expressed the opinion that vibration was a minor ill of the sea, small in comparison with other troubles but, nevertheless, from its dogged perseverence, an abominable nuisance. In the same year, another writer remarked that because a new Royal Yacht—the *Victoria and Albert*—was about to be built the question of vibration had attained a position of national importance, but he thought he was not over sanguine in believing that the matter could be settled for £500!

Returning to the present day, a superficial reading of current literature leaves the impression that the situation with regard to ship vibration is not vastly different from that prevailing in the 1890's. Now, as in those early days, there is considerable difficulty in predicting the behavior of a new design with sufficient accuracy to preclude the possibility of trouble when the ship goes into service, and, more often than not, the vibration specialist is occupied in dealing with vibration troubles as they occur.

This does not imply, however, that small progress has been made in vibration analysis during the intervening years. On the contrary, an ever expanding knowledge of the theoretical and practical aspects of the subject has been an important factor in making possible the astonishing developments in ship and machinery design that have taken place during this period.

At the beginning of this century the steam turbine, with its smoother torque and the absence of large unbalanced reciprocating and rotating masses, was hailed by some as the means for settling the ship vibration problem once and for all.

### TURBINES AND GEARS

Development of the steam turbine for powering the larger ships quickly dispelled this illusion, though the smoother operating characteristics of the turbine directed attention to the propeller shafting. New and difficult vibration problems were encountered, affecting the durability and safety of turbine discs, and blading. In later years, the introduction of reduction gearing between turbine and propeller to increase overall efficiency and extend the use of turbines to ships of lower power, created further vibration problems affecting shaft and gear durability.

Rapid development of the internal combustion engine for marine propulsion in the years immediately after the 1914–18 war also provided many important and urgent vibration problems of which the problem of torsional vibration of crankshafts and propeller shafting was an outstanding example. Indeed, when the Engineering Research Department of Lloyd's Register of Shipping was established about 1935, largely due to the initiative of the Chief Engineer Surveyor, Dr. S. F. Dorey, torsional vibration was one of the first subjects to receive attention under what Dorey himself has described as a campaign for safer shafts.

And in addition to these major items there were a number of important subsidiary matters such as "singing" propellers, axial vibration of propeller shafting, and transverse vibration of engines about their seatings, all demanding the closest attention.

Although, as previously mentioned, it is not yet possible to predict with certainty the overall behavior of a new design, certain aspects of the overall problem, such as torsional vibration of shafting and hull response to excitation of the fundamental modes, can be dealt with in the design stage with some assurance that all will be well on the trial trip and in service.

### VIBRATION OF THE HULL AS A RIGID BODY

An important characteristic of the behavior of a ship's hull in response to periodically applied forces is its capacity for performing heaving, pitching and rolling motions as though it were a rigid body, all at the same frequency as that of the applied impulses. This is a property of all freely supported bodies which, in mathematical terms, corresponds to the zero roots of the frequency equations.

These rigid body motions are generally disregarded in studies of ship vibration because they do not involve any displacement of one part of the structure relative to another. They can, however, impose quite appreciable inertia loads on the hull and engine structures; are often the cause of much physical discomfort among passengers and crew; and they must be taken into account when interpreting vibration records obtained with seismic type instruments.

From the point of view of physical discomfort the rolling component is usually the least desirable and, through the years, several devices have been put forward for dealing with it. One of the earliest was the Schlick gyroscopic stabilizers, introduced about 1904. In this device the gyroscopic forces themselves are used to counteract the roll, the action of the stabilizers being controlled by damping forces applied to the rotor frame. This was not entirely satisfactory because the damping force had to be adjusted to an average value which was not the best for each of many possible operating conditions. An improvement, due to Sperry, overcame this difficulty by using a small pilot gyroscope to control the motion of the main rotor frame in accordance with changing requirements. Sperry gyro-stabilizers were successfully used in many yachts and large vessels. Three 100-ton gyroscopes were fitted in the 48,000 tons gross Italia Line steamship *Conte di Savoia* in 1932. The gyroscopic stabilizer as conceived by Schlick and Sperry did not become really popular, however, probably because of apprehension regarding the serious damage that might occur if the main rotor with its enormous store of energy got out of control.

Nevertheless, the problem of ship stabilization was not abandoned and, as a result of development started in 1935, an elegant solution was produced in the Denny-Brown hydrofin automatic stabilizing gear. This equipment has been described in earlier issues.[6] Briefly, it consists of two retractable stream-lined fins, one on each side of the ship, which can be regarded as a pair of horizontally disposed rudders. When the ship is in motion the flow of water across the stream-line section produces an upward or a downward force according to whether the leading edge of the fin is tilted up or down. If one fin is tilted upwards and the other downwards a couple is produced tending to roll the ship and, by means of hydraulically-operated gear controlled by a small and sensitive gyroscope, the direction and timing of the couple can be adjusted continuously to counteract the roll produced by each wave. The dimensions of the fin and the angular movements necessary to provide the required corrective action are kept to a minimum by providing a flap, hinged to the trailing edge of the main fin, in the manner of the ailerons used in the wings of aircraft. Like an airplane wing this arrangement embodies potentialities of self-excited vibration due to coupling of torsional and flexural modes of vibration when moving through a steady stream of water.

No such troubles have been reported, however, and even if they occurred there are a number of well-known remedies involving no more than a change in the mass-elastic characteristics of the system. The stabilizing fin has already achieved a remarkable amount of success. Over 100 sets were installed in British naval vessels during the last war and, since the war, the equipment has been fitted in many of the largest passenger liners, including the *Queen Elizabeth* and the Royal Yacht *Britannia*.

### ELASTIC VIBRATION

In addition to the rigid body motions just discussed a ship's hull can vibrate in many different modes, determined by the distribution of mass and elasticity along its length. Thus it is possible to produce and sustain severe vibration in practically any hull, given the necessary pulsating disturbance applied at the appropriate number of pulsations per minute to evoke a sympathetic response which may be manifested as vibration involving the whole length of the hull, or may be largely confined to some local position in the hull structure. Sympathetic response, or resonance, occurs when the frequency of any one of the significant modes of natural vibration of the hull coincides with the frequency with which any one of the significant pulsating disturbances is applied. Natural vibration involving the whole length of the hull may occur in the vertical, horizontal or torsional directions and there may be four—and occasionally more—significant modes of vibration in each direction.

The ends of the vessel, i.e., the bow and stern, are positions of large vibration amplitude in all these modes, and there may be intermediate positions where the amplitudes are substantially zero. The positions of large amplitude are called anti-nodes and the positions where the amplitude is substantially zero are called nodes. In the fundamental torsional mode there is one node near the middle of the hull and two anti-nodes. The higher torsional modes have 2, 3, 4, etc., nodes and 3, 4, 5, etc., anti-nodes. In each fundamental bending mode, vertical and horizontal, there are two nodes and three anti-nodes along the length of the hull. The higher modes have 3, 4, 5, etc., nodes and 4, 5, 6, etc., anti-nodes.

There are two principal sources of excitation, the propelling machinery and the propeller. The lower modes of natural vibration, either vertical or horizontal, are most commonly excited by primary unbalanced forces or couples from reciprocating machinery, or by a badly pitched or badly mass-balanced propeller. The theory of engine balancing is now well established and it is possible to determine without much difficulty the magnitudes of the unbalanced couples produced by any given engine assembly. With regard to propeller pitch and mass unbalance, most propellers are now made of bronze with carefully finished blades and it is unlikely that mass unbalance will be very serious except as the result of service damage. Pitch unbalance is more important, because slip-angles are themselves small so that even small variations of pitch from blade to blade can produce considerable variation of individual blade thrust. This can be corrected by differential adjust-

ment of the angles of the individual blades so that the product of the thrust and the radius to the effective center of thrust is the same for each blade. In the cases just discussed the excitation frequency is one cycle per revolution of the crankshaft for engine disturbances and one cycle per revolution of the propeller for propeller disturbances.

The higher modes of vibration, either vertical or horizontal, where there are three or more nodes, may be excited by the secondary unbalanced forces or couples of reciprocating machinery at a frequency equal to twice the r.p.m. of the engine crankshaft; by propeller blade frequency disturbances at frequencies equal to the number of propeller blades multiplied by propeller r.p.m. and integer multiples thereof, due to variation of water flow through the propeller; and by gas forces or reactions in the main engine, principally at frequencies equal to the firing impulse frequency, namely, number of engine cylinders multiplied by engine r.p.m. for two-stroke cycle engines, and one-half the number of engine cylinders multiplied by engine r.p.m. for four-stroke cycle engines.

Generally speaking, the torsional modes are excited by the same engine and propeller forces that excite the horizontal modes of bending vibration.

In geared installations the torque reaction at the gearbox is another possible source of torsional and horizontal bending vibrations of the hull, particularly at engine speeds where there is a strong torsional vibration critical of the shaft system.

Thus there are many possibilities of resonance and the problem is further complicated through the necessity to make sure that no serious hull vibration can occur under the varying conditions of loading and load distribution that may be encountered in service. Depth of water may also have an important influence, particularly on the vertical modes. Operation in restricted waters, such as the Suez Canal, may similarly affect the horizontal modes. Finally, it is desirable to make allowance for the fact that the natural frequencies of the hull tend to become lower as the age of the ship increases.

Figure 1 shows the various possibilities diagramatically, for a hypothetical case. The configurations of the hull in the various modes of vibration are shown at the right-hand side of the diagram. The cross-hatched bands parallel to the base line show the frequency ranges of the various modes, the upper limit applying to the ballast condition and the lower limit to the fully loaded condition. The lines radiating from the origin represent the various excitations. Wher-

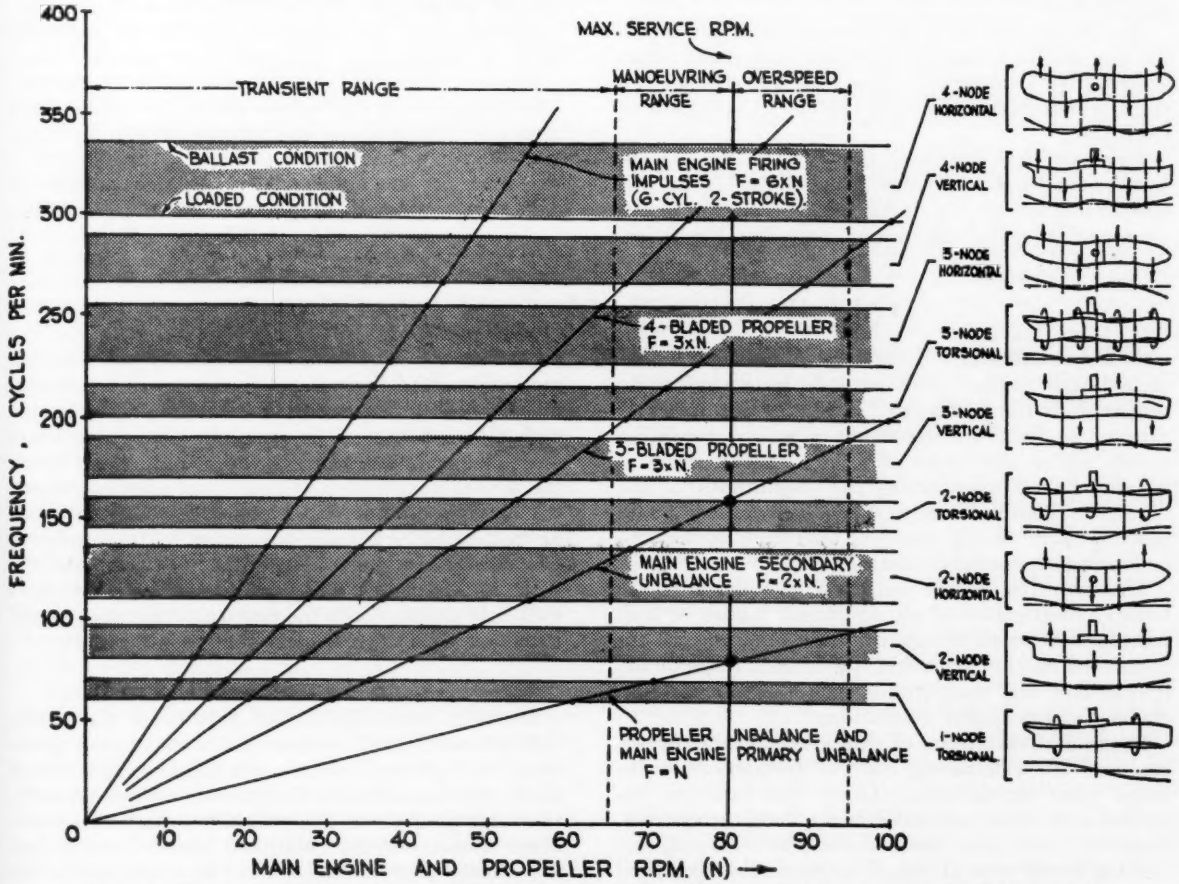



**Figure 1. Diagram showing various possibilities and types of ship vibration likely to be encountered in practice.**

ever an excitation line crosses a frequency band there is a possibility of resonant vibration at some load condition of the ship.

In the particular example shown opposite the following possibilities of resonance at the maximum service speed are indicated: 2-node vertical mode excited by propeller or main engine primary unbalance with the ship fully loaded; 3-node horizontal mode excited by propeller blade frequency disturbances of a three-bladed propeller at an intermediate load condition; 4-node horizontal mode excited by propeller blade frequency disturbances of a four-bladed propeller at an intermediate load condition. There is also the possibility of excitation of the 2-node torsional mode by main engine secondary unbalance, with the ship in the ballast condition, though this is not a very likely source of trouble.

### LOCAL VIBRATION

There are two principal classes of local vibration, namely, local vibration resulting from and accompanying vibration of the hull in one of its natural modes, and local vibration due to sympathetic response of some part of the hull or machinery structures to an excitation which does not necessarily evoke any noticeable vibration of the hull considered as a whole.

The second class of local vibration originates from the fact that in a complex assembly each disturbance searches the structure for a part, such as a panel or a piece of attached equipment, capable of sympathetic response.

This part then functions as a tuned vibration absorber and local resonance occurs. The higher frequency excitations, e.g., unbalanced secondary forces from reciprocating machinery, propeller blade frequency excitations, and excitations arising from the gas forces in the engine cylinders, are the principal causes of this class of local vibration. Of these, propeller excitations are usually the most important, since the propeller is located at an anti-node for all modes of hull vibration.

The amplitudes of local vibrations are not usually very large but, due to their higher frequencies, the accelerations can be sufficiently severe to cause structural damage to the hull and any attached equipment. These relatively small amplitude vibrations can also cause considerable mental distress, leading to fatigue of passengers and crew. Bunyan [1] lists a number of places where experience has shown that local vibration may be specially troublesome. For example, the overhung bridge space of certain tankers is a place where severe local vibration can be excited by almost imperceptible vibration on the strength deck. Masts, samson posts, piping, boilers and other equipment attached to the main hull can likewise be affected. The transverse rocking modes of vibration of engines about their seatings can also cause serious local vibration, especially in large oil engine installations. The exciting forces are usually the transverse reactions on the guides from cylinder gas loads, the engine behaving as a mass mounted upon a relatively flexible diaphragm attached to the frame of the ship.

Bunyan [7] has also directed attention to the possibility of sympathetic response of the rudder to impulses from the adjacent propeller. Even if the natural frequency of the rudder about the rudder head does not coincide with the frequency of a principal mode of hull vibration, it is possible for rudder vibration to attain an amplitude sufficient to cause serious fretting and wear of trunnion bearings and pintles, and damage to the rudder itself.

## PART II — DESIGN STAGE CALCULATIONS

So far as vibration of the ship as a whole is concerned, the design problem can be stated quite simply. It is the problem of matching ship and machinery so that no significant resonant condition occurs within the range of service speeds, while at the same time maintaining the magnitudes of the various excitations below the values which would cause trouble during transient operation in the maneuvering or overspeed ranges.

This requires, on the one hand, evaluation of the natural frequencies of all significant modes of hull vibration under all service conditions likely to be encountered and, on the other hand, knowledge of the frequencies and magnitudes of all significant machinery and propeller excitations.

In the earliest studies of ship vibration the formulas used for calculating natural frequencies were based upon simple beam theory. The hull was regarded as a uniform slender beam, freely supported. Empirical constants were introduced, varying according to the type of vessel, to reconcile calculated and observed values. Provided a new design did not depart too radically from contemporary practice. this method enabled the natural frequency of the fundamental mode of vertical vibration to be estimated with a fair degree of accuracy. In succeeding years more elaborate procedures were introduced in which the actual distribution of mass and elasticity along the hull were taken into account. These were based upon methods originally developed by Rayleigh and Stodola for studying the behavior of beams and the whirling of turbine rotors. At first these procedures took into account only the flexural strain energy and the linear kinetic energy of the vibrating hull.

### THEORY AND PRACTICE

In many cases this yielded results for the fundamental modes of vibration which were in good agreement with observed values, but for the higher modes there was considerable disagreement. Consequently, the basic theory was elaborated to take into account shear strain energy, rotational kinetic energy and the effects of entrained water. In recent years the British Shipbuilding Research Association has un-

dertaken a most thorough examination of the whole subject both analytically and experimentally. Some of the results already achieved are reported in papers by Johnson [8] and Richards [9] of the B.S.R.A. staff. Outstanding matters awating further investigation are the influence of entrained water, particularly with regard to horizontal modes; the effect of structural discontinuities such as riveted joints upon the flexibility of the ship regarded as a continuous beam, since there is reason to believe that the dynamic flexibility is different from the static flexibility, particularly with regard to the higher modes of vibration; the effect of depth of water; and the possibility that certain areas of the deck and double bottom structures may function as tuned vibration absorbers and so produce a significant modification of the principal natural frequencies.

In addition to all these difficulties it must be remembered that comparatively small variations of load distribution, hardly affecting the trim or mean draft, can have considerable effect upon the natural frequencies, particularly those of the higher modes which experience has shown to be the most likely to cause troublesome vibration in the service speed range of larger modern highly-powered single-screw vessels.

When all these considerations are taken into account it becomes apparent that a purely theoretical approach to the determination of even the fundamental modes of hull vibration involves a computing task of formidable size. Even if accurate physical data relating to the hull structure were available in the design stage, the sheer magnitude of the computing task would prohibit determination of numerical solutions to assist matching of hull and machinery, within the time normally available for design.

At the present time, therefore, the main value of these very involved calculations is to assist interpretation of experimental results from existing vessels and thus pave the way toward a better understanding of aspects of the problem which are still somewhat obscure.

### USE OF ELECTRONIC COMPUTERS

There is, however, one way of reducing the labor involved in finding numerical solutions of analytical problems which tend to become more and more complex as knowledge increases, namely, by the use of modern fully automatic electronic digital computing equipment. Such equipment is now in regular use in the aircraft industry for solving in a few minutes vibration problems which formerly occupied experienced mathematicians for period of six months or more.

The proposal to use this equipment for ship vibration work is not new. In a contribution to the discussion of Richard's paper, Lewis [9] described a method of calculation suitable for an electronic computer, and this equipment has been used by the Taylor Model Basin for calculating the natural frequencies of hull vibration, with considerable success. In this country, the Manchester Universal electronic computer [10] has been used for determining numerical solutions to problems of torsional vibration of complex multi-branched geared turbine systems, and whirling of complicated turbine rotor assemblies.

There is a fairly common belief that use of this expensive equipment is only justifiable when a large number of routine calculations have to be performed. While it is true that the speed of routine calculations can be increased several hundred times by this means, the equipment has other equally valuable applications. In research work it provides the means of escape from a tantalizing situation where methods of solution are known, but the numerical exercises necessary to reconcile theory with practice cannot be undertaken because of the magnitude of the computing task. With the aid of electronic equipment, however, there is virtually no limit to the number of exercises that can be performed, once the basic computing program has been established. In design investigations the equipment would enable many tentative solutions to be worked out within the time available for design, to aid selection and indicate trends.

Another fairly common, though erroneous, belief is that only a skilled mathematician can obtain full benefit from the equipment. On the contrary, intelligent application of the equipment for dealing with engineering problems demands a thorough knowledge of practical as well as theoretical implications. There are, of course, certain mathematical procedures best adapted to the smooth functioning of the machine, but these are readily assimilated. It is therefore probable that when the electronic computer comes into general use for engineering applications the preparation of the machine program will be done by an experienced engineer after a short course covering the mathematical aspect of the task.

In the meantime, design stage calculations of hull frequencies must be based upon the best available empirical formulae, aided by experience and judgment. In this connection, Bunyan presents a formula in his recent paper [1] which is stated to provide a reasonably accurate estimate of the 2-node vertical frequency, and factors are given for obtaining approximate values for the higher modes.

According to Bunyan, the natural frequencies of the two- and three-node modes of vertical and horizontal hull vibration can often be predicted with sufficient accuracy to be of value in design stage investigations of the possibility of excitation by primary and secondary external unbalance of reciprocating machinery.

In single- and twin-screw vessels of about 480 ft. or more, however, propeller blade frequency excitation is most often the predominating disturbance and this excites the higher modes of hull vibration. The frequencies of these higher modes were not easy to predict in the design stage, particularly when the hull structure was complicated by the addition of superstructure decks. Nevertheless, attention to single-screw aperture clearances and the blade-tip to hull clearance in twin-screw vessels, in the design stage, should minimize the possibility of trouble.

### DESIGN STAGE CONSIDERATIONS AFFECTING LOCAL VIBRATION

With regard to local vibration, a number of design stage measures can be taken to prevent the drumming, rattling and creaking which is so easily produced in different parts of a ship by quite small transmitted vibrations. Such effects create a greatly exaggerated impression of the severity of the vibration and are often the cause of much mental distress. Attention to the type and rigidity of division bulkheads, particularly in the after part of the ship, and care in selecting, positioning and installing cabin and washroom fittings, with adequate use of vibration insulating materials, are fairly obvious precautions.

All bolts and screws should be firmly secure, with effective locking devices to prevent slackening in service, and if it is not possible to avoid passing pipelines through division bulkheads, the pipes should be supported in rubber or other resilient material to prevent squeaks and groans when relative movements occur.

Main engine and boiler seatings [11] need careful attention with regard to both design and workmanship. Considerable transverse rigidity is necessary and the overall stiffness should be sufficient to prevent local resonant vibration which, in the case of main engine seatings, can result in excessive transverse vibration of the engine excited by crosshead guide reactions. In the case of boilers, local resonant vibration of the boiler about its seating, excited by the propeller, has caused serious damage to superheater and generator tubes and brickwork.

The possibility of mounting the main engine upon a seating having sufficient flexibility to prevent any significant transmission of vibration from the engine to the hull has received considerable attention, and installations using both rubber and steel springs as the resilient elements have been tried in practice, with some success.[12] The theory of vibration isolation is now well-established and there is no great difficulty in designing mounting systems capable of providing excellent characteristics so far as smoothness of engine operation at the design condition is concerned. In large, directly-coupled, main engines, however, the practical use of such systems is prohibited because the amount of flexibility required for a successful mounting system would result in excessive engine movements during maneuvering at reduced speeds, and when the ship encountered even a moderately rough sea.

The practical problems are appreciably easier with the smaller, higher speed, engines used in twin-screw and geared installations, especially where the engine is coupled through a hydraulic or electro-dynamic coupling; but the most attractive field for the application of resilient mountings is that of the auxiliary generator, where the engines operate at constant speed and appreciably higher r.p.m. Slab-type mounting units where the load is carried by a pad of resilient material are not entirely satisfactory because the material tends to consolidate with age and the assembly requires constant adjustment. Assemblies using steel springs, or three-point mountings using bonded rubber-in-shear bobbin-type resilient units of adequate capacity are preferable. Many successful installations of this type have been made and it is rather surprising that more general use has not been made of flexible mountings in this field.

Auxiliary gear, such as feed heaters, strainers, small pumps, valve chests and heavy spare gear, should not be attached to large flat areas such as bulkheads where the cost of the stiffening which might be required to reduce local vibration to tolerable dimensions would be out of proportion to the task it had to accomplish.

In the main hull structure itself every effort should be made to avoid large flat areas of shell plating in way of the stern where they are subjected to the pulsating slip-stream and may vibrate with considerable amplitude at propeller blade frequency. Indeed, Bunyan [1] mentions the desirability of increasing the scantlings of the structure and shell plating of the cruiser sterns of large single-screw vessels as a matter worthy of serious consideration. He cites a case where, during the seatrials of a large single-screw tanker, the vibration was so severe as to cause widespread damage to the internal structure of the after peak.

### RUDDER VIBRATION

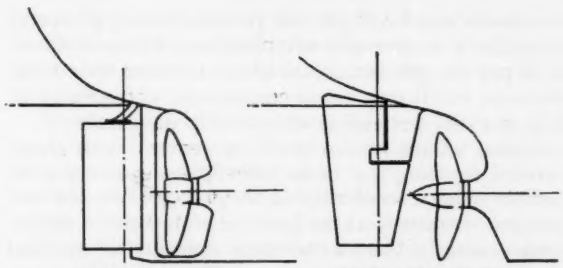
Resonant vibration of rudders is another type of local vibration which has received considerable attention in recent years, notably in the paper by Bunyan already mentioned,[7] based upon experience with streamlined rudders where trouble had been encountered through cracking of welded joints and rudder plating accompanied by damage to pintles and pintle bushes and the coupling connecting the rudder to the stock. In the simplest terms a rudder may be regarded as an elastically suspended mass capable of performing two fundamental modes of natural vibration, namely, torsional oscillations involving twisting of the stock and bending oscillations involving flexure of the suspension system. If, as is usual, the center of gravity of the rudder is offset from the hinge line the inertia force due to transverse bending oscillations produces a couple about the hinge line tending to cause torsional movements. Similarly the inertia couple due to torsional oscillations about the center of gravity produces a force at the hinge line tending to cause flexural movements. In other words the torsional and bending modes are coupled with the result that the natural frequency of the lower coupled mode is less than the natural frequency of the lower uncoupled mode, and the frequency of the higher coupled mode is greater than the frequency of the higher uncoupled mode.

Resonant vibration of the rudder can occur at either of these coupled frequencies, given an appropriate excitation. However, in a conventional rudder assembly, where the rudder is hinged to a rudder post at several points along the hinge line and is also supported by a shoe at the bottom, the flexural stiffness is considerable and the possibility of serious bending vibration within the operating range would appear

to be remote. There remains the possibility of torsional vibration, weakly coupled with the bending mode, excited by impulses from the adjacent propeller. This might become troublesome under resonant conditions, when the frequency of propeller excitation, i.e., number of propeller blades multiplied by propeller r.p.m., coincided with the natural frequency of the rudder. Apart from the possibility of serious damage to the rudder and its attachments, this type of local vibration situated, as it is, at an anti-node for all principal modes of hull vibration, might be the cause of serious transverse vibration of the hull considered as a whole, especially if the frequency of rudder vibration coincided with the natural frequency of a transverse mode of hull vibration. Under these circumstances troublesome local vibration might also be experienced in deck houses, samson posts, masts, derricks and funnels, particularly with structures of all-welded construction where the inherent damping is appreciably reduced.

Bunyan recommends [7] that from the point of view of avoiding vibration, rudder design should be based upon the principle of placing the natural frequency of the rudder above the maximum operating speed. Factors which assist in this direction are a short stiff stock to provide the maximum possible stiffness and an overall design which provides the smallest possible mass moment of inertia consistent with efficient functioning. It should be remembered, however, that even if the rudder resonance is above the operating speed range when the ship is new, damage to the rudder in service might result in flooding, thus producing a reduction of natural frequency sufficient to bring the resonance into the service speed range. This possibility can be prevented by filling the rudder with a light non-inflammable plastic such as the type used in the hollow blades of steel air screws where the filling is inserted in the plastic state and is subsequently cured by heating to form a light but relatively rigid support for the blade surfaces. Such treatment would not only prevent flooding but, by supporting the plates against panting vibrations, would prevent damage from that cause.

Another consequence of the coupling of torsional and bending modes is the possibility of self-excited vibration or flutter. This can occur when the rudder is moving through a steady stream of water without any extraneous periodic disturbance to excite vibration. It is due to a combination of the flexural and



Original design 'Clear Water' design

**Figure 2. Rudder designs for the 'Mariner'-type ship.**

angular displacements which results in variations of the angle of attack in a manner which abstracts energy from the stream of water to maintain vibration, once it is initiated. The phenomenon occurs at a definite stream velocity relative to the rudder, known as the flutter speed, and it can be initiated by a variety of causes such as the momentary disturbance which occurs when the ship makes a rapid turn. The existence of a definite flutter speed depends, among other things, upon the fact that when the rudder deflects under the combined effect of torsion and flexure, hydrodynamic forces are introduced which are proportional to the angle of twist. Thus the effective stiffness controlling rudder vibration is made up of two parts, the elastic stiffness of the stock and the hydro-dynamic stiffness introduced when the rudder deflects. The hydro-dynamic stiffness, and therefore the overall value, varies with the velocity of the stream. At the flutter speed the resultant conditions become favorable for abstracting energy from the stream to maintain vibration. Flutter is most likely to occur when the coupling between the torsional and bending modes is strong, i.e., when the two natural frequencies are close together. Preventive measures include a design which provides the greatest possible rigidity in both torsion and flexure while maintaining the torsional and bending frequencies as far apart as possible so that the coupling between the two modes is weak.

The conventional type of rudder assembly shown on the left-hand side of Figure 2 would appear to be less susceptible to flutter than the "clear water" or suspended design shown at the right-hand side. A great deal depends, however, upon the stiffness of the attachments to the rudder post in the conventional design. In particular if appreciable wear occurred in these attachments, conditions favorable for flutter might be introduced.

## PART III — REDUCING THE EXCITATIONS

The overall problem of ship and machinery vibration is so complex that it would be extremely optimistic to expect, even with full benefit of present-day knowledge, that all resonances of the general and local structures could be foreseen and provided for in the design stage.

It is therefore desirable to investigate the possibility of limiting the magnitudes of all significant excitations to values which will ensure that the corresponding disturbances are within acceptable limits, even under resonant conditions.

From a survey of published information it would appear that over the range of frequencies applicable to ship investigations, say from 60 to 600 cycles per minute, acceleration rather than amplitude affords the better measure of the severity of vibration. A

value of about 0.3 ft. per sec. per sec. is very good and is unlikely to provoke complaints; a value of about 1 ft. per sec. per sec. is not likely to cause structural damage, but it may cause complaints; and a value of 3 ft. per sec. per sec. is structurally dangerous.

These values are in good agreement with those quoted by Bunyan [1] from investigations on some 60 vessels where accelerations of 1.0 to 0.75 ft. per sec. per sec. measured at the position of maximum amplitude—usually the stern—were normal for vertical and transverse vibrations respectively.

At these values there was little danger of damaging the main hull structure, though there might be local vibration of sufficient amplitude to require attention, and there might be complaints of fatigue and mental discomfort from passengers and crew. Accelerations of 3 ft. per sec. per sec. were liable to cause damage, particularly at points of high stress concentration in the structure.

### PROPELLER EXCITATION

It is fairly safe to say that if an analysis of reports of troublesome ship vibration published during the last 60 or 70 years was made, propeller action would be revealed as the most outstanding cause. Improved methods of propeller manufacture have largely eliminated troubles due to pitch or mass unbalance. But, no matter how carefully the propeller is produced, excitations at propeller blade frequency and integer multiples thereof remain, since they are largely dependent upon extraneous causes. These relatively high frequency forces are available not only for exciting general and local vibrations of the hull, but they are also an important cause of axial and torsional vibration of propeller shafting. This is not surprising when it is remembered that the propeller is situated at an anti-node for all modes of ship and shafting vibration, where the forces are most effective in exciting vibration.

### PROPELLER TROUBLE IN IMPORTANT SHIPS

The literature contains many accounts of troubles due to propeller-excited vibration, including such famous ships as the *Lusitania*, *Mauretania*, and *Queen Mary*. But one of the most interesting cases was that of the 67,000 ton quadruple-screw Atlantic liner *Normandie*. As the result of disagreeable vibration in the after part of the ship during her first trials in May, 1935, which did not respond to first-aid treatment by additional stiffening of the decks where the vibration was most intense, a very complete investigation of the problem was undertaken.[13] The vibration extended over about one-third of the length of the ship from the stern, with a frequency equal to the number of propeller blades (3) multiplied by propeller r.p.m. Various remedies were tried including changing the direction of rotation of the two wing propellers, which reduced the amplitudes by about 20 per cent but had an adverse effect upon the handling properties of the ship; synchronizing the four propellers through special synchronizing gear working on the engine governors, which was disappointing and unreliable; and fitting special stanchions with spring-loaded steel and lignum vitate friction surfaces designed to absorb vibration energy, which produced no worthwhile improvement. The measures eventually adopted consisted of fitting an expansion joint in the sun-deck near the stern; fitting new shaft bossings of improved form and greater strength; fitting new four-bladed propellers; and installing additional girders and strengthening frames and beams in the lower decks. These modifications reduced the vibratory amplitudes to about 20 per cent of those originally recorded, and in some areas there was no detectable motion.

This and other examples from both single and multi-screw ships have so clearly demonstrated the importance of the propeller and its immediate surroundings in relation to ship vibration that analytical and experimental investigations of the subject have been in progress for many years. Much valuable information has been gathered, but the problem is so complicated that no general rules have yet been formulated to enable a quantitative assessment of the magnitudes of propeller disturbances, or of their effects upon the hull, to be made in the design stage of every new project. It is possible, however, to lay down certain recommendations, based upon accumulated knowledge and experience which should assist towards avoiding the pitfalls most likely to be the cause of serious vibration trouble on the trial trip. This simply means that the person best qualified to guide propeller design, with regard to both performance and the vibration problems involved, is the propeller specialist himself. The days when the design of a propeller was apt to be regarded as just another item in the engine designer's tally of responsibilities are over, at any rate so far as the more advanced types of vessel are concerned. Indeed, it is highly probable that the majority of ships have been reasonably free from serious vibration troubles, just because there has been an adequate measure of co-operation among everyone concerned.

The intensity of propeller excitation in single-screw ships depends greatly upon the characteristics of the water flow through the propeller disc, the wake velocities tending to reach peak values in the upper part of the aperture. Adequate clearance between propeller and aperture is therefore of primary importance, too little clearance between the propeller tips and the stern frame arch and between the trailing edges and the rudder post being particularly significant in relation to both vertical and transverse vibration.

The sketch (Figure 3) from Bunyan's recent paper,[1] is based upon model and full scale tests on a number of vessels, and shows the recommended minimum aperture clearance for achieving minimum propeller-excited hull vibration in single-screw installations with prevailing designs of stern frames and rudders, and without measurable loss of propeller performance. Other factors affecting performance, vibration, and liability to cavitation-erosion are number of blades, r.p.m., and blade skew-back and pitch variation, e.g., "wake adapted" screws.

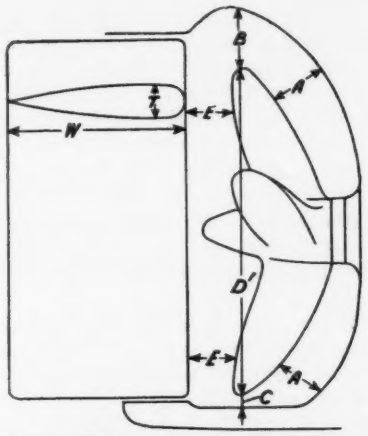



**Figure 3. Single screw aperture clearances.**

| Position | Clearance |
|---|---|
| A = | 0.15 × D feet |
| B = | 0.10 × D feet |
| C = | 0.03 × D feet |
| E = | 0.08 × D feet or T feet, whichever is the greater. |

The same general considerations apply in multi-screw installations. The principal requirements are after-body and propeller bossings designed to provide the smoothest possible inflow; adequate clearance between propeller blade tips and hull structure; and adequate structural stiffness in the plane of the propeller disc, where the pulsating forces are strongest. The excitation arises from passage of the outer portions of the propeller blades through the slower moving boundary layer which hugs the ship's side. The thickness of this boundary layer, and therefore the tip clearance necessary to minimize the excitation, is a function of the length of the vessel. This is the basis of the formula devised by Troost for determining the desirable minimum clearance, namely, Clearance = $(0.11L^{1/3}-0.36)$ ft., where L is the length on the waterline, in feet. It is of interest to note that in the case of the Royal Yacht *Britannia*,[14] the length on the water line is 380 ft., so that according to the above formula the minimum desirable clearance between blade tips and hull is about 22 inches or 0.18D, where D is the diameter of the four-bladed propeller. The actual propeller tip clearance is 33 inches or 0.27D.

The troubles which developed in H.M.S. *Warspite* and other naval ships both here and in the United States, directed attention to the possibility of serious propeller excited vibration during maneuvering of multi-screw ships due to the slip-stream of an outer propeller interfering with the blades of an inner propeller.[15]

Similar trouble, though probably to a lesser extent, can arise from any cause which results in water entering the propeller disc at an angle to the plane of rotation of the propeller. This occurs, for example, when a ship is turning, and in installations where the shafting is raked or splayed so that the axis of rotation of the propeller is inclined to the direction of water flow.

Trouble of this kind has been experienced in aircraft during pull-out from a dive, when skidding or side-slipping during a turn, or when the total power of a twin-engined machine was not equally divided between the port and starboard engines. In all these cases the result is an angular flow of air through the propeller and the condition is called yaw-excitation. The effect of the non-axial flow is to produce periodic variations of the effective angle of incidence of the blades as they pass obliquely through the airstream. The overall result is to produce an unsymmetrical load which excites flexural vibration of the airscrew blades and nodding and whirling motions of the hub, at a frequency equal to airscrew r.p.m. The effect is, in fact, similar to that produced by pitch unbalance.

Ship vibration from this cause is not likely to be very serious, however, except in the case of slip-stream interference, already mentioned, in which case some alleviation might be obtained by an appropriate arrangement of the relative positions of the propellers.

### MULTI-SCREW SHIPS

Another type of vibration, peculiar to twin- and multi-screw vessels, occurs when the excitations from the individual engines of propellers build-up and die away periodically due to slight periodical changes in the r.p.m. of the individual units. This hunting phenomena is not usually serious from the point of view of structural damage—indeed, a small periodical variation of speed has more than once been suggested as a means for preventing resonant vibration—but it can be very trying to passengers and crew and is sometimes more fatiguing than a sustained vibration of greater maximum amplitude. Several quite successful synchronizing devices have been developed for dealing with it, and the variable pitch propeller is particularly suitable for this type of speed control. But the problem does not appear to have become sufficiently acute to encourage the general adoption of synchronizing devices.

## PART IV — ENGINE EXCITATIONS

As already mentioned, the theory of engine balancing is now well-established and in many cases it is possible to achieve a substantial reduction of primary unbalance either by fitting crankweb counterweights or, in multi-cylinder internal combustion engines, by selecting a favorable firing order. Care is necessary when applying these remedies, however, since they might have a serious effect upon the torsional vibration characteristics of the shafting. A system of heavy counterweights, for example, might

reduce the natural frequency of a significant mode of torsional vibration by an amount which brings a severe shaft critical into the service speed range.

Similarly, a firing order, favorable from the point of view of engine balance, might be undesirable from the point of view of torsional vibration.

In most cases, however, it is possible to determine an acceptable compromise, though the task is sometimes difficult because although acceptable limits for torsional vibration are now fairly well known, there is still insufficient information on the amount of engine unbalance that can be tolerated. The subject is a difficult one involving, among other things, the response characteristics of the hull for various service conditions and the influence of engine location on the effectiveness of the excitation. During recent years investigations of the fundamental aspects of the problem have been initiated, notably by Lloyd's Register of Shipping and the British Shipbuilding Research Association, using portable vibration-exciting equipment capable of imposing pulsating forces of known magnitude of various parts of a vessel. Some of the results already obtained are reported by Johnson [8] and Richards.[9] In reply to the discussion on his recent paper,[1] Bunyan expressed the opinion that forces up to $\pm 6$ tons and couples up to $\pm 250$ tons ft., would not be troublesome as a transient condition, provided the service speed itself was well removed from any hull critical. On the other hand, much smaller disturbances could cause trouble if they excited a hull critical at or near the service speed. Bunyan cited an example where the 2-node mode of hull vibration was excited near the service speed in a 480 ft. tanker in the deep loaded condition, by a triple expansion steam engine having an unbalanced primary force of less than one ton and an unbalanced primary couple of about 100 tons ft. The vibration was reduced to acceptable limits by fitting crankweb balance weights giving a resultant moment about the after node which balanced the resultant moment of the engine masses about the same point.

As in the case of propeller excitations there are a number of general rules which can be used as a guide in the design stage.

### EXTERNAL UNBALANCE

The principal sources of engine-excited vibration involving the whole length of the hull are the *externally* unbalanced primary and secondary forces and couples. Theoretically, an engine with an unbalanced force is incapable of exciting general hull vibration if it is located at a node, where the amplitude on the hull deflection curve is zero. Conversely, an engine with an unbalanced couple is theoretically incapable of exciting general hull vibration if it is placed at a point on the hull deflection curve where the slope is zero, i.e., at a position approximately mid-way between two nodes.

Thus, for the two-node mode of vibration, an engine installed amidships where the deflection is large but the slope is zero, is more likely to cause serious vibration if external forces rather than external couples are unbalanced; while if installed at or near the after node where the deflection is zero but the slope is large, external couples rather than external forces are likely to be troublesome. If the engine is installed aft of the after node, where both deflection and slope are appreciable, both forces and couples are capable of exciting vibration, and of the two the force is usually the more effective, e.g. in a 450 ft. vessel a force of about $\pm 1$ ton is roughly equivalent to a couple of $\pm 150$ tons ft. if both are applied near the stern.

Though these rules are not strictly true, due to the effect of local deformations of ship and engine structures, they are useful when attempting a qualitative assessment of engine balance.

In the case of multi-cylinder internal combustion engines having three or more cylinders with the crankpins spaced at equal angular intervals round the crank circle there are no externally unbalanced primary or secondary forces.

This simplifies the problem somewhat, though there may be residual primary and secondary external couples of sufficient magnitude to be troublesome. In many cases it is possible to reduce both primary and secondary residual external unbalance to acceptable values—in some cases to zero—by an appropriate choice of firing order, though, as previously noted, this possibility is conditioned by the need to make sure that the chosen firing order is satisfactory with regard to torsional vibration, crankshaft manufacture, and main bearing loadings. Where it is not possible to reduce the unbalance in this way, the primary unbalance, which is often the most troublesome, can be reduced by fitting crankweb counterweights. Here again the effect of the added masses on torsional vibration must be investigated.

### FLYWHEEL EFFECT

In some cases they may have a beneficial influence on torsional vibration, e.g., where the flywheel effect of the added mass is sufficient in itself to provide good starting and maneuvering characteristics, thus enabling a heavy flywheel to be discarded.

The unbalanced rotating parts can be completely counterweighted, but the unbalance due to the reciprocating parts, which acts only in the vertical plane, can only be eliminated by overbalancing in the horizontal plane, or by fitting a system of gear-driven counterweights which rotate at engine speed and produce a counterbalancing force in the vertical plane only. Gear-driven counterweights are rarely, if ever, used, however, since in cases where the vertical mode of vibration is so strongly excited that it is necessary to counterbalance both revolving and reciprocating parts, the horizontal mode is sufficiently removed from the service speed range to permit overbalance in that plane.

Residual secondary forces and couples, which are due to the obliquity of the connecting rod and act only in the vertical plane, can only be neutralized by fitting a system of gear-driven counterweights rotat-

ing at twice crankshaft speed. Devices of this type have been used in extreme cases with some success, but they are best avoided. It is better to obtain some relief by reducing the weight of the reciprocating parts as much as possible in the design stage.

Incidentally, crankweb counterweights have the advantage, even in engines where the residual external unbalance is negligible, that they improve the *internal* balance of the engine by reducing the unbalance of each cylinder individually. This reduces the stress and strain on the engine structure and its seating, which assists in preventing local vibration.

### VIBRATION INVESTIGATIONS ON EXISTING SHIPS

The design of a new ship is an enterprise where the closest attention must be given to problems of dynamics and vibration if serious breakdowns involving costly delays and modifications are to be avoided. As the preceding discussion shows, a great deal is now known about the various possibilities of trouble, and methods of dealing with them have been worked out. But there are still so many uncertainties, particularly with regard to physical data, and some of the essential calculations involve so much numerical computation, that it is not yet possible to be absolutely sure that all will be satisfactory on the trial trip.

Nevertheless the knowledge and experience accumulated from the work of research establishments and individual investigators should enable the grosser pitfalls to be avoided. Further work on such problems as the effect of entrained water and local structural flexibilities on natural frequencies, together with mechanization of the computing processes for finding numerical solutions will assist towards placing the subject upon an even firmer foundation.

In the meantime, as Bunyan remarks in his recent paper,[1] the sea trial of a new ship nearly always discloses some regions of the structure where additional stiffening is desirable. In many cases these are blemishes rather than real faults, troublesome because of their effect upon the comfort of passengers and crew, rather than because they are structurally dangerous. A great deal can be done with the aid of modern methods of sound-proofing and vibration insulation; the matter being one of finance rather than engineering.

Occasionally, however, troubles are revealed, either on the trial trip or in service, which demand immediate attention. The task of the vibration specialist is then to diagnose the cause and prescribe the speediest possible remedy. Thanks to a vigorous and progressive electronics industry a vast array of equipment is now available to assist in this task, including the ubiquitous resistance wire strain gauge which, if skilfully used, can measure the strain in remote parts of the structure inaccessible to other means, and in the rotating and reciprocating parts of the machinery. It can also be used in rough weather and is therefore suitable for measuring the stresses and strains under the most adverse of operating conditions.

A fully instrumented program is always desirable for fundamental studies, and is sometimes the quickest way of resolving certain detail problems such as investigations of local vibration where the symptoms are elusive.

But, as Bunyan and other have amply demonstrated, there are many cases where a great deal can be learned by intelligent observation. In some cases observation alone has enabled the cause to be identified and the remedy to be prescribed; in other cases preliminary observation has directed more detailed investigation into the channel most likely to yield a profitable result. Observations should be made systematically and the following helpful suggestions, from Bunyan's paper, are well worth noting.

(*a*) Observe the engine r.p.m. at which the troublesome vibration is most pronounced. This is usually a fairly straightforward task, since the critical conditions are generally well defined.

(*b*) Observe the direction of the vibration, whether principally in the vertical or transverse directions. The steering flat or the forecastle are good positions for observing any of the principal modes of general hull vibration, which are usually the most strongly excited.

(*c*) Observe the frequency of the vibration by counting the number of cycles per minute, preferably with the aid of a stop watch. It is quite possible to count up to 500 per minute by the simple procedure of making a pencil dot on a piece of paper for every ten cycles.

(*d*) Observe the positions of the nodes and antinodes, i.e., the positions of minimum and maximum vibration along the length of the hull. This can be done by setting the engine r.p.m. to the critical value and maintaining this condition throughout the tests. Starting aft and working forward the positions of little or no vibration and the positions of maximum vibration should be marked on the strength deck. Experience indicates that it is often possible to obtain agreement within $\pm 5$ ft. from two or three independent observers.

(*e*) Observe the nature of any local vibration, to decide whether it is due to vibration of the hull as a whole in one of its principal modes, or whether it is due to some other cause. It frequently happens, for example, particularly with large superstructure vessels, that the propeller or engine excites local vibration at a frequency which does not correspond to the frequency of a principal mode of hull vibration.

Higher frequency excitations are also a known cause of local vibration and these can generally be distinguished by the fact that variation of main engine r.p.m. does not affect the vibration. The source of these vibrations can sometimes be traced by observing the effect of shutting down various auxiliary machinery, one by one, starting with the auxiliary generators. This is best done in port with

a quiet ship, and the object is to find an excitation having a frequency which coincides with the frequency of the observed vibration. In difficult cases, involving the higher frequencies, the task may require the use of instruments.

It is of fundamental importance to determine the true nature of any local vibration before deciding the remedy. If, for instance, the vibration is the result of vibration of the hull as a whole, then local stiffening will not be the best solution and attention will have to be given to the possibility of modifying the excitation. If, on the other hand, the vibration is a local resonant condition, then local stiffening might well be the best solution.

(*f*) Observe the r.p.m. at which any hammering of the steering gear occurs and also the r.p.m. at which there is any hammering of the tail shaft in the stern bearing. This information assists in deciding whether the vibration is propeller or engine-excited, and whether a resonant condition of the rudder is a contributory factor.

The observations should be made in good weather conditions and there should be little or no movement of the rudder. The results should be plotted on a diagram of the type shown in Figure 1 and notes should be made of any peculiarities of the installation under investigation, such as whether the rudder or propeller has suffered damage; whether structural damage has been observed in any part of the hull; whether the troublesome vibration occurs only under a particular service condition; and whether the engine has suffered any derangement affecting, for example, the distribution of power among the cylinders.

### TYPES OF VIBRATION ENCOUNTERED IN SERVICE

In the discussion on his recent paper [1] Bunyan enumerated the predominating types of vibration encountered in service in order of prevalence and severity, as follows:

1. *Types of Vibration:*
   - (*a*) Propeller-excited fundamental modes, vertical and transverse, involving the length of the hull.
   - (*b*) Engine-excited fundamental modes, vertical and transverse, involving the length of the hull.
   - (*c*) Local vibrations in way of the stern of the vessel.
   - (*d*) Local vibrations in bridge structure, affecting navigation instruments, radar and radio communications.
2. *Types of Vessel:*
   - (*a*) Single-screw tankers, particularly vessels over 500 feet in length.
   - (*b*) Singlescrew vessels with machinery aft.
   - (*c*) Single-screw vessels with machinery midships.
   - (*d*) Twin-screw vessels.

The larger single-screw tankers can present severe vibration problems, particularly where propeller apertures are tight, though there have been many coasters where severe main engine-excited criticals have been troublesome.

3. *Loading Condition:*

The ballast condition was perhaps the worst condition, but fortunately it is often possible to remove the criticals from the service speed by "tuned" ballasting. The load distribution of ballast should be in accordance with the recommendations of the Classification Society, but slight variations might be necessary for tuning in way of the last three tanks, care being taken to keep longitudinal stresses in the hull within approved limits.

Practical examples are always one of the most valuable features of engineering text-books. They are at once a testimonial to the writer, and an encouragement to the student.

It is therefore not surprising to find that Bunyan devotes a substantial part of his paper [1] to examples which illustrate the practical application of vibration theory to hull and machinery problems. The topics of principal interest are summarized in the following paragraphs.

### TUNED BALLASTING

Adjustment of ballast in tankers has proved a useful means for removing a vertical or transverse hull critical from the service speed.

This expedient is based upon the simple principle that adding or subtracting weight at an anti-node reduces or increases the natural frequency of the hull, while changes of weight at a node have no significant effect upon frequency.

In applying *tuned ballasting* in tankers it is necessary to know the nodal position in way of the last three tanks, just forward of the poop. It is then possible, by making use of these three tanks, to produce a frequency variation sufficient to remove the critical from the service speed.

Tuned ballasting is not of much value, however, in the case of a loaded tanker operating at a strong propeller-excited critical, since the peak tanks are small compared with the main tanks and, in any case, it is often not convenient to operate with ballasted peak tanks.

Cargo vessels also do not respond very readily to tuned ballasting, due to the widely varying cargo loading conditions under which they operate.

### PROPELLER MODIFICATIONS

Where a strong propeller-excited hull critical occurs at the service speed, cropping the propeller blades up to 7 per cent of the diameter permits the engine r.p.m. to be increased in approximately direct ratio, with little or no loss of efficiency. This is a very useful temporary expedient which might even be acceptable as a permanent remedy, depending on whether or not cavitation erosion develops, whether the increased engine speed is permissible from the point of view of torsional vibration in the shaft sys-

tem, and whether the increased inertia loading on the moving parts of the engine is acceptable or not.

The expedient of cropping the propeller blade tips has also been applied with satisfactory results in many cases of propeller-excited local vibration, where a reduction of the magnitude of the excitation is required. The magnitude of the excitation depends greatly upon aperture clearances, especially if these are smaller than the values indicated in Figure 3, in which case a comparatively small increase of clearance can produce a considerable reduction of excitation.

### SPEED INCREASE TO MAINTAIN POWER

The only practical methods of increasing the blade tip to stern frame arch clearance in an existing ship are cropping the propeller blades or fitting a new propeller of small diameter. When using this expedient to reduce local vibration, however, it must be remembered that engine r.p.m. are increased in proportion to maintain the same power. It must, therefore, be verified that the increased engine r.p.m. does not bring the new service speed closer to a hull critical which was originally above service r.p.m. If this happens the vibration, though reduced in magnitude, might remain troublesome. If, on the other hand, there is a hull critical below the original service speed, then the alteration will be beneficial both on account of the reduced magnitude of the excitation and because the service speed is moved further away from the critical.

Bunyan cites the case of a 25,000-ton s.d.w. tanker where cropping 0.045R off the propeller blade tips reduced the amplitude of a serious critical to about one-third its original value.

The propeller trailing edge to rudder post clearance can also be a source of severe excitation if it is appreciably smaller than the value given in Figure 3. In a particular case cited by Bunyan, three sister ships had each suffered rapid tailshaft failures accompanied by repeated failures of the holding down bolts in the thrust seatings, due to axial vibration of the shafting. The propeller-excited hull vibration had a resultant acceleration of about 7.6 ft. per sec. per sec. with an original propeller trailing edge clearance of only 0.045D. Increasing this clearance by 3½ in. resulted in reducing the acceleration to about 1 ft. per sec. per sec. The leading edge to propeller post clearance was ample, enabling the increased trailing edge clearance to be obtained by fitting a new tailshaft 3½ in. shorter than the original. The three ships have now been in operation for about two years with this modification and in each case there has been no measurable loss of efficiency.

In other cases increased trailing edge clearance has been obtained by cutting away part of the leading edge of a finned rudder post and, in one instance, by also trimming back and fairing 2½ in. off the trailing edge of the propeller blades in way of the tightest part of the aperture.

Where a new propeller is to be fitted, some variation of propeller pitch or a change in the number of blades are permissible methods for removing a troublesome critical from the running range. Many examples are to be found where changing from three to four blades has produced most beneficial results, and in recent years a number of cases have occurred where as many as five or six blades have been used with advantage.

### MACHINERY MODIFICATIONS

When troublesome hull vibration is due to primary external unbalance of reciprocating machinery, the magnitude of the excitation can be reduced by installing a system of crankweb counterweights and this has the further advantage that it reduces the magnitude of the internal unbalance.

This modification, however, has the disadvantage that it might involve considerable delay and expense, especially with awkwardly shaped crankwebs; and space limitations might prohibit fitting balance weights of the necessary size.

Furthermore, the effect of the additional mass on the torsional vibration characteristics of the shaft system must be carefully investigated—cases on record where existing balance weights have had to be eliminated because of torsional vibration. A simple alternative, described by Bunyan and Hildrew in a previous paper [16] consists of a single balance weight fitted to the propeller shaft as far aft as possible—the further aft the smaller the weight and the smaller its effect upon torsional vibration—and this has been successful on a number of occasions. Compared with crankweb balance weights, however, this device has no effect upon the internal balance of the engine and would therefore not be effective in cases where local vibration was due to distortion of the engine structure and its supports, through the action of the individual cylinders.

Secondary external unbalance of a reciprocating engine cannot be reduced by a simple system of balance weights attached to the crankwebs or propeller shaft, but requires a system of gear-driven balance weights running at twice engine r.p.m. Devices of this type have been used with fair success on a number of occasions but they are apt to develop troubles of their own and are best avoided.

It is better to seek a solution by lightening the reciprocating parts of the engine as much as possible or by reducing the propeller diameter to permit the service speed to be moved from the critical condition.

Transverse vibration of the engine about its seating, excited by the reactions of the engine crosshead-guides, is sometimes troublesome. Since it arises from the flexibility of the ship's structure under the engine considered as a whole, little can be done to reduce it by any reasonable amount of stiffening of the seating itself. A simple remedy which has been found effective in a number of cases, mostly on tankers but a few on midship installations, is to provide bracing struts between the engine and the ship's side. It is desirable to introduce a shear-pin or similar device to minimize the damage which would otherwise occur to the engine in the event of a collision.

During the discussion on Bunyan's paper [1] the

problem of transverse vibration of the engines of small single-screw shallow draft craft was mentioned. The trouble is apt to develop when the engine power exceeds about 500 b.h.p. and appears to be due to the difficulty of providing an engine seating of the depth required to ensure adequate stiffness, while at the same time keeping the propeller shaft at a sufficiently low level to ensure adequate propeller immersion. The possibility of dealing with this situation by introducing gearing between the engine and propeller shafts was mentioned, but it was considered that this was a matter which could only be settled for each case individually since there were a number of somewhat conflicting requirements to be met.

In twin-screw installations two types of transverse vibration of the engine about its seating can occur, namely, a swaying mode in which the engines vibrate in phase, and a tuning-fork mode in which the engines vibrate out-of-phase. The tuning fork mode is generally the easier to excite since, like vibration of the prongs of a tuning fork, the motion is largely reactionless so far as the mounting is concerned and this implies that comparatively little energy is dissipated by the engine seating. Very severe vibration of this type has therefore been reported in a number of cases, but the remedy, fortunately, is fairly simple, involving only tieing the engine entablatures together by strong cross-beams.

The swaying type of vibration is comparatively rare. It involves appreciable distortions of the engine seating and is therefore more heavily damped. Where troublesome vibration of this type is encountered, the remedy is to tie one or both engines to the ship's side, taking care to protect the engines from damage in the event of a collision, as in the case of single-screw installations.

Finally, Bunyan describes an unusual but interesting case where violent hammering at the thrust block was experienced through coincidence between a resonant axial vibration, excited by the propeller, and axial vibration excited by an engine torsional vibration critical. In this case the trouble was overcome by rotating the propeller relative to the crankshaft through one intermediate shaft bolt pitch, thus destroying the cumulative effect of the two excitations.

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# *BREATHING MEDIA IN DEEP SEA DIVING*

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In 1827 THE deep sea diving suit was invented by Siebe, an Englishman. Today the suit, a closed dress made of heavy waterproof canvas, is essentially the same. But scientific knowledge since that time has added many refinements which have increased the limits of mans' ability to dive and work beneath the sea.

An important phase of this problem and one in which much new knowledge has been gained is the breathing media used by the diver.

The use of air is satisfactory as a breathing medium for diving to depths of 150 feet. It is easily supplied by means of compressors or air flasks. No special equipment is required for compressing the air. The only requirements are that the air be oil free and that no noxious gases be permitted to accumulate near the inlet to the air compressor.

At depths greater than 150 feet, however, a physiological phenomena occurs. The mental faculties of the diver begin to dull. This effect becomes so serious that when divers reach depths beyond 200 feet, many of them are unable to perform even the simplest tasks. In many cases, speech becomes incoherent. Euphoria sometimes occurs. The limit of descent for the average diver on air is about 300 feet. Practically every subject becomes unconscious at 350 feet.

To illustrate the mental effect of air at depths of 150 feet or more, an interesting experiment was carried out using the yeoman attached to the Experimental Diving Unit, Naval Gun Factory, Washington, D. C. Being an expert typist, he could best demonstrate the efficiency of mental and physical coordination. He was placed in the recompression chamber with his typewriter arranged so that he could breathe through a mask and at the same time copy a standard typing exercise. Under a pressure corresponding to 200 feet, the yeoman copied from an exercise book for five-minute periods, first breathing air and next breathing a helium-oxygen mixture.

Upon completion of the tests he stated that he felt he had done better when breathing air. Actually he made nearly three times as many errors while breathing air, even to the point of skipping whole lines. Yet his sense of well-being on air, similar to intoxication, made him believe that he had done well during that period, while he was quite aware of having made some errors when breathing helium-oxygen.

There can be no doubt that the peculiar mental effect experienced when man is exposed to high air pressure is caused to the greatest extent by nitrogen. As shown in the preceding paragraph, the use of a nitrogen-free breathing medium practically eliminated the previous effects of air. The breathing of helium-oxygen also reduced the sense of pressure to about one-fourth that of air. Dives have been made to a depth of 561 feet using helium-oxygen mixtures with very little impairment of the mental faculties.

The narcotic effect of nitorgen is comparable to an anesthetic. This effect is dependent on the relative solubility of the breathing gas in oil and water, according to the Meyer-Overton theory. Meyer and Overton suggest that anesthetics act upon the lipoids

of nerve cells, rendering them more fluid, and thus changing their relation to the other constituents of the cells. The derangement of the physical condition of the cells impairs their function and narcosis results.

The oil-water solubility ratio (solubility in oil/solubility in water) for nitrogen and helium are 5.24:1 and 1.7:1 respectively. Thus the narcotic or anesthetic effect of the nitrogen would be much more pronounced.

It was suggested that part of the narcosis may have been due to other causes than the solubility of the respective gases in oil and water. Since the molecular weight of nitrogen is 28 and that of helium is 4, this effect may have also been due in part to the difference in the molecular weights. To explore this theory, a quantity of argon gas was procured, which has a molecular weight of 40. The divers tested in these experiments were trained men of exceptional stability. Their experience in breathing air at pressures up to 10 atmospheres ranged from 5 to 20 years. One atmosphere is equal to a depth of 33 feet of sea water. As a result of this experience, they had long been accustomed to the progressive stupefaction and neuromuscular impairment induced by air as the pressure is increased from 1 to 10 atmospheres. Moreover, the divers were proficient in estimating their diving depth usually well within 50 feet of the actual depth by their subjective reactions.

The tests were conducted in such a manner that the divers did not know either their actual depth or the nature of the medium breathed. They were asked to state their depth on the basis of previous experience in high air pressure environments. At actual depths on argon ranging from 90 to 130 feet the subjects reported depths approximately 1.7 times as great. When air was substituted for argon at the same depths, the mental fogginess cleared to such a degree that the subjects thought they were being brought to the surface.

The great depressant action of argon in comparison with nitrogen indicates that the molecular weights probably do influence the effects of helium, nitrogen and argon as breathing media. The results of the above experiment are also in accord with the Meyer-Overton law, argon being twice as soluble as nitrogen.

The question naturally arises why oxygen alone could not be used as the breathing medium. The physiological effects of oxygen under pressure supplied to a diver are even more sensational than those of air. Oxygen is toxic at high pressure, acting chiefly on the central nervous system. Some symptoms of oxygen poisoning are nausea, lip twitching, vertigo, euphoria, sleepiness, vomiting, and visual disturbances, which terminate in the dangerous state of convulsions if the subject is not immediately switched to air. Twitching of the facial muscles, especially around the mouth, is commonly known as the "end point," after which a convulsion is certain to follow if the subject is not immediately given air. Recovery after breathing air is rapid. If air were not supplied, the subject would become unconscious and die.

These symptoms usually take place when the diver is at a depth where the partial pressure of oxygen is 2.3 atmospheres absolute or more. Thus the maximum depth that should be used with pure oxygen is about 50 feet. This is under conditions of rest and then only for a limited time. Activity would reduce this depth at which oxygen can be used as a breathing gas. It is obvious from the above that oxygen is not suitable as a breathing medium under pressure.

When the oxygen-helium mixture is used for the breathing gas in deep sea diving, the percentage of oxygen must be so that its partial pressure does not exceed 2.3 atmospheres absolute. This is merely the recapitulation of Dalton's law of partial pressures whereby the pressure exerted by a mixture of gases is equal to the sum of the separate pressures which each gas would exert if it alone occupied the whole volume. For example, if a dive is made to a depth of 330 feet, which is equivalent to 11 atmospheres absolute, the maximum oxygen percentage in the mixture is obtained by dividing 2.3 by 11. This gives an oxygen percentage of 20.9%. It is advantageous to use the maximum oxygen percentage because it reduces the recompression time. The dominating effect on the diver is that of the partial pressure of the helium, and any reduction in the latter would produce a situation where less recompression is required. This is as indicated by Henry's law whereby the amount of gas which a liquid will dissolve is directly proportional to the pressure of the gas. This holds true for all gases that do not unite chemically with the solvent. The solvent in this case are the tissues of the diver.

The use of pure oxygen in the final stages of decompression is standard procedure in oxygen-helium diving. This involves the application of Dalton's and Henry's laws. At present, the diver is placed on pure oxygen when he reaches 50 feet. The partial pressure of helium in the lungs of the diver is then zero. When this situation exists, the elimination of the helium from the tissues is at a maximum since the rate of gas elimination is a function of the partial pressure of the ambient gas. In this way, the decompression time is decreased.

From these observations, it could be anticipated that helium-oxygen mixtures would prove satisfactory for depths in excess of 150 feet. It is interesting to note that a mixture of oxygen and hydrogen has been used successfully in dives in some of the European countries. However, the explosive nature of this combination precludes its widespread use. This mixture was tried because helium was not available, the United States being the only country that has helium in quantity.

One of the problems confronted in helium-oxygen deep sea diving is the accumulation of carbon dioxide in the helmet. If it is not eliminated by sufficient ventilation or some absorption process, it will be inspired by the diver. This causes carbon dioxide symptons if the effective concentration is greater than 3%.

In normal breathing, the carbon dioxide which is deposited by the blood in the lungs is about 5.3%. As

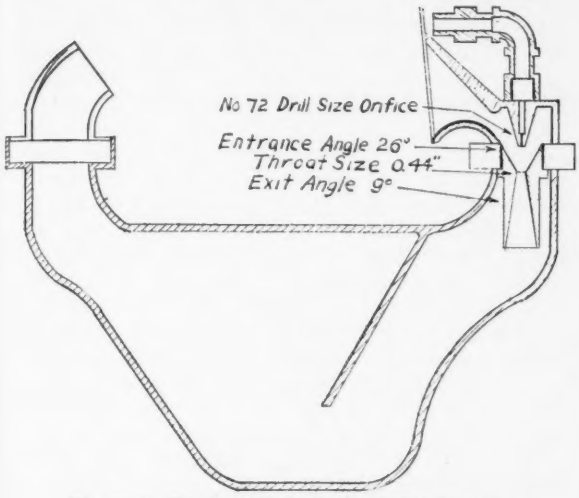


**Figure 1. Sketch of $HeO_2$ Recirculating System**

breathing proceeds, fresh air is taken into the lungs and is mixed with the air in the lungs. Upon exhalation, the mixture which is released will contain somewhat less than 5.3% of carbon dioxide. With each breath the carbon dioxide is washed out of the lungs so that the amount left is always about 40 mm. partial pressure. Through automatic features in what is called the respiratory center through which the blood flows, the depth of the breath and the number of breaths per minute are regulated so as to maintain the partial pressure of the $CO_2$ in the blood and the partial pressure in the lungs nearly constant.

If air containing 4% $CO_2$ were breathed at atmospheric pressure it is easy to see that a great increase in lung ventilation would be necessary in order to keep the $CO_2$ in the lungs at 5.3%. If we breathed air containing more than 5% $CO_2$ we would soon find that no amount of ventilation would keep the lung $CO_2$ down to 5.3%. This would result in severe panting followed by collapse.

The physiological effect of gases present in the air breathed depends on their partial pressure. Hence the volume per cent of $CO_2$ in the inspired air that can be tolerated is inversely proportional to the absolute pressure. Thus at a depth of 264 feet, or 9 atmospheres absolute, 0.33% of $CO_2$ would have the same physiological effect as 3% would have at the surface. If a man is breathing air in a confined space at one atmosphere and the $CO_2$ builds up to 1 or 2%, he may not notice the change in breathing. If, however, this space were suddenly compressed to several atmospheres, this same percentage that was hardly noticeable before would now become intolerable. It is therefore imperative in diving that the effective carbon dioxide percentage remain as low as possible.

In order to keep the $CO_2$ concentration within satisfactory limits, it is necessary to ventilate the helmet at a rate of from 1 to 4.5 feet per minute. The latter value is necessary when the diver is performing hard work on the bottom.

To use this volume of helium-oxygen gas per minute would require very large reserves. This would obviously be most impractical and especially so when diving is performed from a ship. It would also be expensive. Furthermore, the work necessary to mix these huge amounts of gas would produce a labor and storage problem. The gas is mixed by splitting a full bottle of helium into an empty one. Following this, the oxygen is added from another bottle to the desired percentage. Since it is necessary to determine the oxygen percentage within 0.5%, the oxygen content of each bottle must be tested. This is done by means of a Haldane or Pauling analysis apparatus. Clearly then, the amount of labor to mix gas for one deep dive would be prodigious.

In order to reduce the amount of gas used, it was necessary to develop an apparatus that would use less gas and at the same time remove the excess carbon dioxide, remove the excess moisture and provide make-up oxygen for that consumed by the body. The first consideration was the oxygen, for in addition to making certain that the diver has enough oxygen to sustain life, it was highly desirable to keep up the oxygen partial pressure so as to prevent the increase of partial pressure of the helium that controls the decompression requirements. Calculations showed that a half a cubic foot (14 liters) of gas containing not less than 15% oxygen would sustain life in a man doing fairly hard work.

A closed circuit which would return the exhaust gas to the surface for revitalization would be impracticable. The first thought was to provide the diver with supplementary equipment somewhat resembling a rescue breathing apparatus, including a compressed supply of oxygen-helium mixture. This idea was abandoned in favor of purifying the gas contained in the diver's dress by forcing it through a chemical absorbent.

In the rescue breathing apparatus a mouthpiece is employed whereby the lung pressure is used to accomplish the circulation. In order to avoid the use of a mouthpiece and yet maintain a forced circulation it was suggested that the oxygen-helium supply which provides the make-up helium-oxygen be used as the driving agent in an aspirator to force the helmet gas through the absorbent without effort or attention on the diver's part.

The standard hose and fittings were retained. A small hose was led from the regular hose on the supply source or surface side of the control valve. With this arrangement the driving gas was led to the jet described below, with the control valve closed. Should the diver require a sudden additional supply of gas as in descending, he has merely to open his control valve.

The aspirator, or the recirculating system, is a venturi tube, into the throat of which a jet is fitted having an orifice so proportioned that with 50 pounds per square inch differential pressure, a volume of helium-oxygen gas is introduced which is sufficient to replace the oxygen consumed in respiration. At the

same time, the venturi tube forces a volume of gas from the helmet through the cannister and back into the helmet. The excess gas that tends to accumulate escapes through the exhaust valve. By means of this recirculating system the diver is given sufficient ventilation and uses only about one-fifth of the amount of gas that would be required using normal ventilation.

In the beginning, soda lime was used as the absorbent, but experience showed that it did not absorb the moisture. This excess moisture not only fogged the face plates of the helmet, but also dampened the soda lime which reduces its effectiveness and allowed carbon dioxide to build up.

Shell Natron, a caustic potash mixture in shell form, is now used and is quite satisfactory. It has a strong affinity for moisture and for this reason will not deteriorate when exposed to air. One pound has been found to last three hours with the diver at rest and 30 minutes doing hard work. Approximately three pounds of Shell Natron are used in the cannister. Although this may seem insufficient for a long dive, it is enough because the decompression time limits the time spent on the bottom to about 30 minutes. This of course varies somewhat with the depth. The remainder of the time is spent in decompression and this can be considered rest.

With the improved recirculation system, it is now possible to go to depths of at least 561 feet with no danger of excessive carbon dioxide.

It is the opinion of the medical authorities in this field that man is physiologically capable of descent to a depth of 1000 feet without any ill effects, provided he were decompressed properly. But it is doubtful that dives in excess of 600 feet will ever be practical. At present satisfactory and practical decompression tables have not been completely formulated. This would require a great amount of experimental work. Following this field tests would have to be made. It has been found that more bends always occur in actual dives than in the experimental ones made in a pressure tank. But it is certain that in deeper dives the amount of decompression time would be prodigious in comparison to the time spent on the bottom. A 10 minute dive at 600 feet would require approximately 4 hours of decompression. These dives would clearly be only observation dives with no time left for actual work, even though the diver was physically and mentally capable of performing work.

In addition to the decompression problem there are other difficulties encountered in deep dives. Visibility at great depths is very poor, especially if the bottom is muddy. The diving hose has to be of such great length that even moderate currents tend to sweep the diver off the bottom. This might cause him to blow up to the surface. This fast ascent would almost certainly be fatal because of gross bubble formation in the body. Any equipment or hose failure might also be fatal to the diver. The diver is aware of this and hence the psychological climate for extremely deep dives is not favorable.

ADOLF G. STRANDHAGEN AND WILLIAM G. SOMMER

# AN ELECTROSTATIC METHOD OF EXCITING THE NATURAL MODES OF VIBRATION IN BLADES

**THE AUTHORS**

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## INTRODUCTION

CERTAIN TECHNICAL problems arising from the vibration of gas turbine blades and of marine propellers have become of increasing importance in recent years. Gas turbine blades can fail if the frequency of the aerodynamic forces is near the important resonant natural frequencies of the blade. In the marine field, propellers can "sing" if the frequency of the hydrodynamic forces are very near the natural frequencies in torsion and bending. Thus there is a need for practical determinations of natural frequencies and natural modes of vibration so that large amplitudes of motion and singing may be avoided.

There are basically two methods of approach to this vibration problem. The first is the analytical computational method. This method of solution presents complexities since it depends upon expressions which involve the variable thickness, the non-symmetrical contour, and the helical form of blades. In any but the most simple cases, these expressions are very complicated. The final results and interpretations are dependent upon the complete solution of a set of dependent or coupled differential equations which involve these complex expressions. In most cases, a solution is impractical if not impossible.

The second approach to the problem is the experimental method. This method, in contrast to the first, provides two advantages. First, it allows the natural modes of vibration to be determined practically while in motion. Second, it suggests a simplified electronic device for measuring these vibrations.

## METHODS OF BLADE EXCITATION

It is clear that the experimental method is a practical one to use if any quantative information is to be obtained. In the past a number of these methods have been developed by various research workers in this field. A brief description of these previous methods of blade excitation will be presented before any theory is discussed.

The crudest method of excitation is that of bowing. In this method a bow, such as a violin bow, is drawn across the edge of the blade. This causes the blade to vibrate. The natural frequencies can then be measured by analyzing the noise generated by the motion of the blade. This method is used chiefly for finding the lower modes of vibration, since the higher modes are rapidly damped. (1)

A more extensively used system is that of pneumatic excitation. In this system air is blown onto the surface of the blade from a specially designed nozzle. Vibrations can then be excited if the spacing between the blade and the nozzle is suitably adjusted. However, as in the bowing method, the higher modes of vibration are not easily excited. (1)

However, the most common method used today is that of electromagnetic excitation, which may be broken down broadly into two types. These are the transducer method and the eddy-current method. (1)

The transducer method uses a modified loudspeaker as the exciter. In this method the speech coil is directly coupled to the blade root. When the loudspeaker is driven by an audio-frequency oscillator, the blade can be set into vibration at any desired frequency. The range, in this case, is extended to 10,000 cycles per second, but the power requirements are in the range of 1,000 watts. No readily available apparatus can be used that will supply such a high power requirement.

The eddy-current method makes use of an alternating magnetic field. In this case a force is produced by the magnetic field which causes the blade to vibrate. Although this method increases the frequency range considerably, the efficiency of the system is very poor, and large sources of power are required. These power requirements are in the range of 1,000 watts.

These are the four main methods of approach to the problem. They are all deficient because of higher power requirement needed or because only the simpler modes of vibration can be detected. (1) Moreover, the apparatus for these methods is also either very crude or very expensive.

### THEORY OF ELECTROSTATIC METHOD

Thus far, the problem of determining the natural modes of vibration for gas-turbine blades has been discussed and the current methods of solution to this problem have been considered. It was found that these methods all possess certain disadvantages. In contrast, the electrostatic method of excitation overcomes these disadvantages to a large extent.

Basically, the electrostatic method is straightforward. Vibration of the blade is accomplished by placing it near a metal block. The block is so designed that its fundamental natural mode is much higher than any mode of the blade. If a potential is placed across these elements, a charge will be produced on their surfaces. This charge will be positive on one element and negative on the other. For example, the blade will be charged positively, while the block is charged negatively. Since unlike charges attract, a force will exist between them. If the block is rigidly mounted, the blade will be deflected.

If a sinusoidal variation of potential is used, the problem becomes more complicated. Since the charge existing on the blade and block is directly proportional to the potential, the amount of charge will also vary sinusoidally. Hence, the force, being proportional to the square of the charge, will cause the blade to vibrate as the square root of a sinusoidal forcing function. This relationship between the force and the voltage may be computed by considering the mathematical derivation.

If it is assumed that the surface of the blade and the block are perfectly conducting, that a linear distribution of charge exists on their surfaces, and that the effective spacing and area are constant, it is evident from Coulomb's Law (3) that:

$$F=\frac{1}{4\pi\varepsilon_o}\int\frac{Q^2}{D^2}dA \qquad (1)$$

where F is the force, Q is the charge on one of the surfaces, D is the spacing between the elements, A is the effective area, and $\epsilon_0$ is the dielectric constant of a vacuum. If this equation is solved for the force, it is found that:

$$F=\frac{v^2\varepsilon_o A}{2D^2} \qquad (2)$$

This gives the general expression relating the force to the voltage, where v is the voltage.

If this potential is a sinusoidal variation, then:

$$F=\frac{(V_m\sin\omega t)^2\varepsilon_o A}{2D^2} \qquad (3)$$

where $V_m$ is the peak voltage. Simplifying this:

$$F=\frac{\varepsilon_o A V_m^2}{2D^2}\sin^2\omega t \qquad (4)$$

which is equivalent to:

$$F=\frac{\varepsilon_o A V_m^2}{2D^2}\left(\frac{1-\cos 2\omega t}{2}\right) \qquad (5)$$

This expression may be simplified to give:

$$F=\frac{\varepsilon_o A V_m^2}{4D^2}-\frac{\varepsilon_o A V_m^2}{4D^2}\cos 2\omega t \qquad (6)$$

Examination of this solution reveals some very important facts. Placing a sinusoidal potential between the blade and the block has the effect of producing a constant force between these two elements equal to:

$$F=\frac{\varepsilon_o A V_m^2}{4D^2} \qquad (7)$$

This means that since the block is rigidly mounted, the blade will be deflected from its manufactured position towards the block by a constant amount. The blade will not be driven around this new mean by a force:

$$F=-\frac{\varepsilon_o A V_m^2}{4D^2}\cos 2\omega t \qquad (8)$$

or:

$$F=\frac{\varepsilon_o A V_m^2}{4D^2}\sin\left(2\omega t-\frac{\pi}{2}\right) \qquad (9)$$

which shows that the oscillating part of the force lags the exciting potential by ninety degrees.

This solution has revealed two facts which may be used to determine the type of components necessary for the system. First a sinusoidal input gave the solution of equation (6). Since the second term on the right-hand side of this expression is the type of force required, an alternating current source is obviously necessary.

The first term on the right-hand side means that the blade will be deflected toward the block by a constant amount. To counteract this undesirable effect, a force given by the negative of equation (7) is required. Since the only variable in this expression is $V_m$, a direct current source is necessary.

However, some method must also be developed to observe the motion of the blade and an arrangement made for holding the blade and block rigidly.

### DESIGN OF THE SYSTEM

From the previous discussion, it is evident that four components must be designed. These are an alternating current source, a direct current source, an observing-measuring device for the vibrations of the blade, and a mounting for the blade and block. However, before considering the design of these devices, an examination should be made of the whole system.

Figure 1. is a block diagram of the system showing the four components which must be designed. Each component may now be considered as a part of the system. This will allow both the requirements of the system and the specifications of the individual components to be determined at the same time.

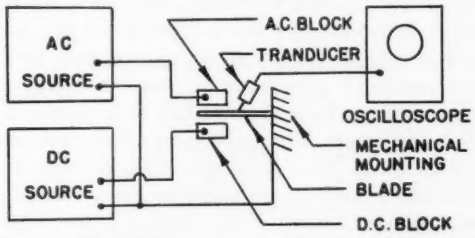


**Figure 1. Block diagram of apparatus showing essential components.**

In order to consider the alternating current source, it is necessary to examine the characteristics of the blade. The mechanical construction of the type of blades to be studied is such that the frequency range of this alternating potential should be from 20 cycles per second to 7,500 cycles per second at a magnitude of approximately 5,000 volts r.m.s. (1) The current requirements will be less than 5 milliamperes because of the high impedence of the blade and block assembly. This impedence will have a minimum value in the range of 2 megohms. The distortion of the potential should also be kept to a minimum.

The blade, DC block, and the direct current source shown in Figure 1. were found to be necessary in order to counteract the constant attractive force obtained from the alternating current potential. Because of the magnitude of this alternating potential, the direct current source should be variable and capable of a maximum of 8,000 volts. The potential should also be constant, and the ripple content kept to a minimum. The design will be simplified, however, since the blade and block are an open circuit to direct current. This means that no load current is required.

A method is also needed for observing the motion of the blade. Since the vibrations are relatively high in frequency and the displacements very small, visual observation is impossible. As a result, a device must be designed which will allow these observations to be made. There are three types of systems which can be used. They are an optical system, a sound system, and an electrical system. (2) Only one of these, however, is economically feasible as a starting point for the design. This is the electrical system which embodies a phonograph-type transducer for converting the motion to an alternating potential, and an oscilloscope for observing this potential. (1) These are shown in Figure 1.

Moreover, the blade and block mounting exhibited in Figure 1. must hold these elements in position. This requires a universal type of assembly, since the blades vary both in length and in root dimensions. The blocks should be movable so that the forces can be applied at any point along the length of the blade. The spacing between the blade and block must also be adjustable, and the entire mechanical assembly rigid while in use.

*Alternating Current Source*

In approaching the design of an alternating current source, two types of devices can be considered. These are an alternating current machine and an audio oscillator. Primarily, machinery is too high in cost and it is not readily available for the required output specifications. In contrast, an audio oscillator is low in cost and is readly available, but its maximum output potential is only in the range of 100 volts.

If we assume that an audio oscillator is to be used, some type of device is necessary for amplifying the output of the audio oscillator to the required 5,000 volts. This device must give the amplification with a minimum of distortion, and couple the oscillator and load. Because of the capacitive nature of the blade and block assembly, transformer coupling to the load is also necessary. Resistance and direct coupling are not feasible. (4)

The required voltage amplification can be obtained by use of either vacuum tube amplifiers or step-up transformers. However, it was found that by the use of a combination of these, satisfactory results could be obtained using readily available standard electrical parts.

Moreover, several power amplifier and transformer combinations may also be operated in parallel with the secondaries of the transformers connected additively in series. A single transformer for this situation is again not a standard type, but the use of several transformers offers a better solution. Power transformers of the 60-cycle type can be used. These meet the required frequency range and step up the voltage without introducing too much distortion. A single transformer does not have the required step-up, but two power transformers, with their secondaries in series, are more than sufficient.

Figure 2. is a diagram of the alternating current

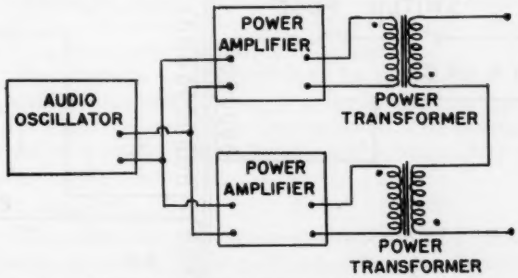


**Figure 2. Block diagram of A.C. source.**

source used. The audio oscillator is a Hewlett-Packard model 205A. This model has a maximum output of 100 volts at five watts to a matched load and a frequency range of 20 cycles per second to 20,000 cycles per second. The output voltage and frequency are variable. The harmonic content of the output is very low and an output impedence control is provided for varying the output impedance to match the oscillator to its load.

The power amplifiers are of the standard type. Figure 3. is a schematic diagram of one of these. This type of amplifier is capable of passing the required frequency range without introducing a considerable amount of distortion.

The power transformers, as stated previously, are of the standard 60-cycle type. They are Navy Model CRV 30810 transformers, having a tapped 105, 115, and 125 volt primary winding, and a center tapped 3,200 volt secondary winding. These were found to meet the required frequency range without introducing an objectionable amount of distortion. As can be seen from Figure 2., the primaries are each supplied by separate amplifiers and the secondaries are connected additively in series.

*Direct Current Source*

From the previous mathematical derivation, it became apparent that a counteractive force would be required in order to equalize the constant portion of the force obtained from the alternating current potential. This force is to be obtained by placing a direct current potential across a second block and the blade. The direct current source must deliver a maximum of 8,000 volts; it must be variable, and must have an output with a very low ripple content. It need supply no load current.

There are three methods by which this type of direct current potential might be obtained. They are direct current machinery, a 60-cycle step-up transformer type of supply, and a television-type high voltage supply.

The first two of these methods of approach are very expensive to build. The third type of supply, however, offers a much more economical solution. In this type an oscillator generates a sawtooth voltage of high frequency, which is amplified and passed to a flyback transformer, the primary of which acts as an auto-transformer. This gives the required high voltage. (5) The transformer itself also has a secondary winding, which in conjunction with a field coil and damper tube, converts the voltage obtained from the secondary winding to a direct current potential. This




**Figure 3. Schematic diagram of power amplifier.**

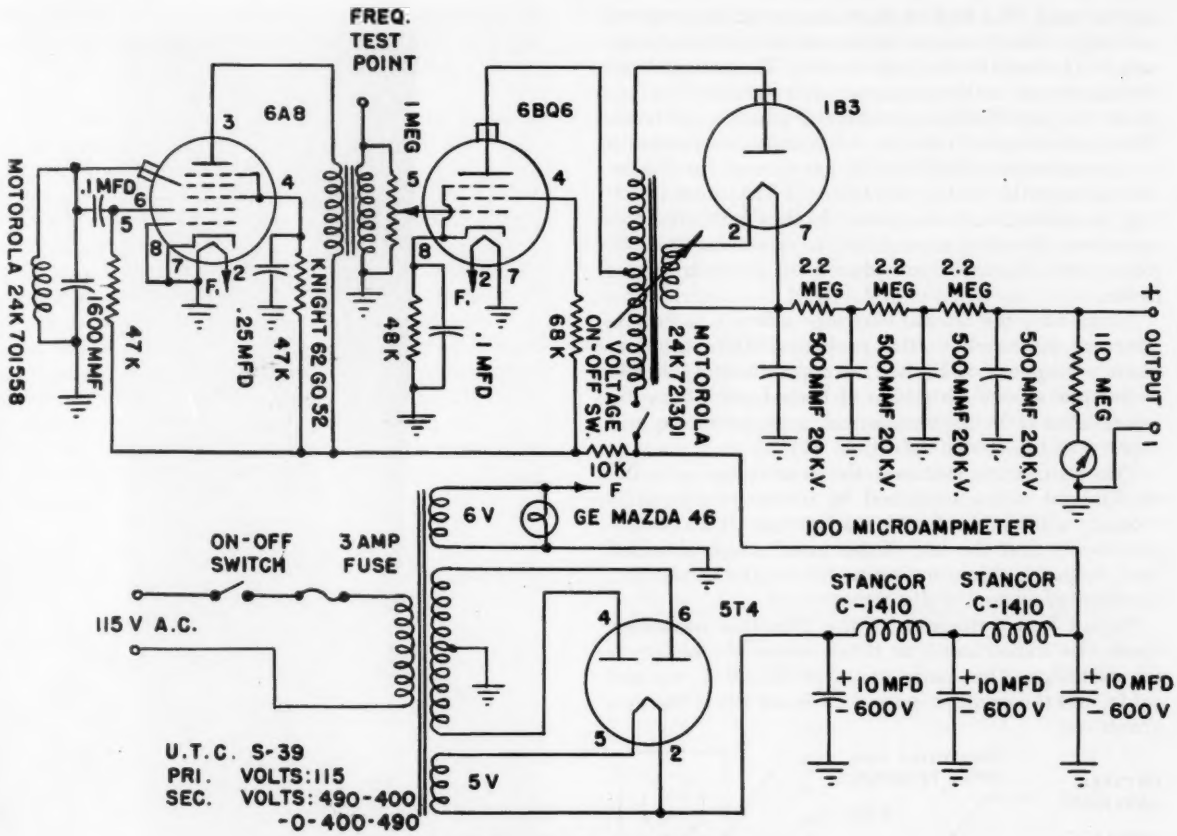


**Figure 4. Schematic diagram of D.C. source.**

potential is then used to supply the plate requirement of the oscillator and the power amplifier.

The high voltage obtained from the primary of the flyback transformer is rectified by a standard high-voltage rectifier tube, such as a 1B3 or a 1X2. The voltage is then filtered by a resistive and capacitive type of network. The value of the capacitance required is small in this case because of the high frequency and high resistance used. The condensers are usually of a value of 500 micromicrofarads, at 20,000 volts and the resistors, two megohms at one-quarter watt. These parameters are standard, low cost units.

The advantage of this type of direct current source is its ability to supply very high voltage at low ripple content. The principal disadvantage is instability due to the fact that the plate voltage for the oscillator and power amplifier is obtained from the flyback transformer.

As an alternative, a modified type of television high-voltage supply seems most desirable. This system should use an oscillator, power amplifier, flyback transformer, rectifier, and filter, as before. However, the secondary winding of the flyback transformer cannot be used and the plate voltage should be supplied by a standard type of power supply. This eliminates the instability, while retaining the other advantages of this type of system.

Figure 4. is a schematic diagram of the direct current supply used. The oscillator generates a sine wave and uses a 6A8 penagrid tube. The tuned circuit uses a Motorola 24K701558 horizontal oscillator coil.

The power amplifier itself is a conventional type, using a 6BQ6 pentode tube. The input voltage to the power amplifier is variable, so that the output can be adjusted. Coupling between the oscillator and the power amplifier is accomplished by means of a standard interstage transformer. The plate voltage requirement is supplied from the power supply and the output of the power amplifier is coupled to the flyback transformer.

The flyback transformer, a Motorola type 24K721301, is used as an auto-transformer. The core is arranged so that the reluctance of the magnetic path can be varied. This allows the maximum output of the direct current source to be preset.

Rectification is accomplished by means of a 1B3 rectifier tube and filtering is accomplished by means of a resistive and capacitive network. The output is read on a 10,000 volt voltmeter and contains 0.35 per cent ripple content.

*Vibration Converter*

The vibration converter is composed of a phonograph-type transducer and an oscilliscope. Considering first the transducer, there are several types which

can be used. The first of these is a capacitive type of cartridge, which has an almost unlimited frequency range, (1) but is very high in cost. The second type of transducer is the magnetic cartridge used extensively in high-fidelity record reproducing systems. This type of transducer has a frequency response up to approximately 20,000 cycles per second, but has an output potential that is very low. (7) This means very high amplification is necessary. In this particular use extensive shielding is required to overcome the objectionable distortion introduced by the extraneous fields.

In this case the crystal cartridge offers a more satisfactory approach to the problem. While the frequency response is limited to approximately 10,000 cycles per second, this type of transducer offers the advantages of being economical, easy to obtain and replace if it becomes defective. (7)

The connection between the transducer and the oscilliscope is accomplished by means of two individually shielded leads twisted together. It was found previously that the use of the usual single shielded lead, with the shield acting as the return conductor, resulted in excessive distortion.

Figure 5. is a diagram of the vibration converter itself. The transducer is an Electrovoice Model 7 crystal cartridge; the leads are type RG29/U coaxial cable, and the oscilliscope is a Dumont 304 H Oscillograph.

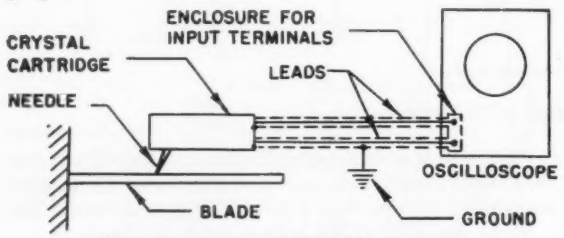


**Figure 5. Diagram of vibration converter.**

The entire unit is completely shielded except for an eight-inch hole, through which the needle protrudes. The case of the oscilliscope, the enclosure for the input terminals of the oscilliscope, the shield of the coaxial lines, the universal-type mounting, and the case of the crystal cartridge, are all connected to ground. This is necessary to eliminate the distortion caused by the electric and magnetic field produced by the high voltage.

*Blade and Block Assembly*

In addition a device is needed for mounting the various types of blades that will be tested, for positioning the blocks, and for holding the crystal cartridge so that the needle will rest on the blade. This device must also be rigid and provide the necessary electrical connections.

In Figure 6., an example of the specific type of blades to be studied is shown. A table-top type of vise offers an effective method of rigidly clamping this type of blade. A false set of jaws is grooved to take the blade root, and a screw-down type of electrical terminal is attached to one of the false jaws. The vise

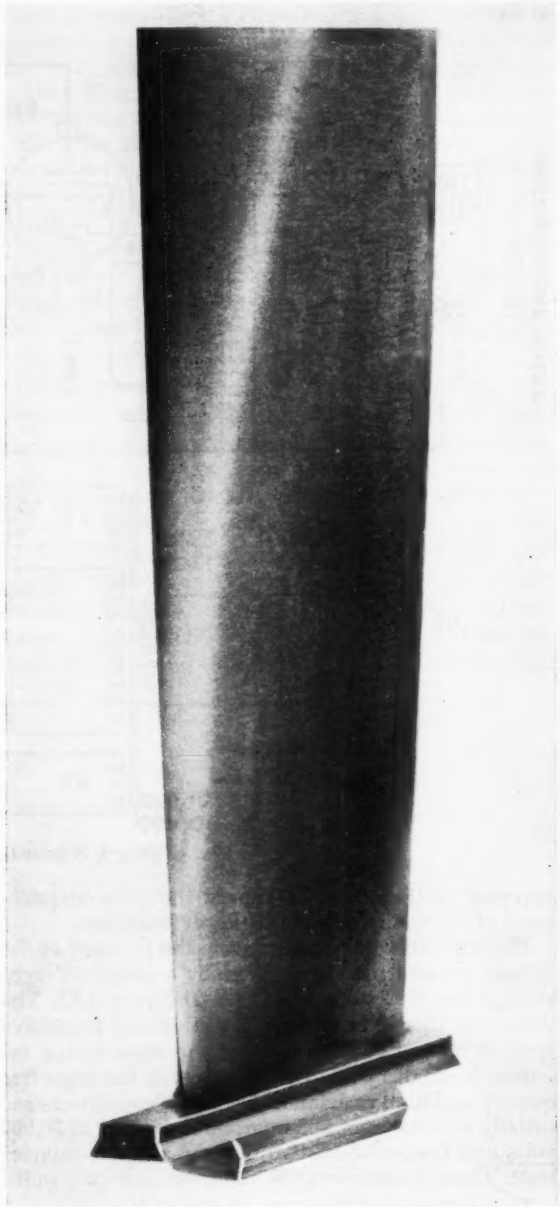

**Figure 6. A typical gas-turbine compressor blade.**

is bolted to the base used for mounting the entire assembly.

The blocks themselves are mounted by means of L-shaped brackets. The front vertical surface is faced to take the side of the block, and is also slotted for the bolt fastening the block to the bracket. This arrangement allows the block to be moved back and forth in the slot to adjust the spacing. The base of the L-shaped bracket is fastened to a slot in the base by means of a guide. This allows the block to be moved to any position along the length of the blade. The blocks also have screw-down type terminals for the electrical connections.

The crystal cartridge mounting is so constructed that the needle of the crystal cartridge can be positioned at any point in any plane. The assembly is made of a vertical rod coupled to a horizontal rod. By moving the horizontal rod up or down the vertical rod, any horizontal plane can be obtained. The horizontal rod can then be rotated to any angle in the plane, and tilted at the position selected. The end of the horizontal rod is fitted to mount a standard type of crystal cartridge.

The entire blade and block assembly must be freely suspended since extraneous vibrations are transmitted to the blade through the base and vise if a direct contact is made with any other surface. These extraneous vibrations distort the vibrations produced by the alternating current potential. The suspension is obtained by the use of a two-inch thick pad of sponge rubber, having the same length and width as the base. This blade and block assembly is shown in Figure 7.

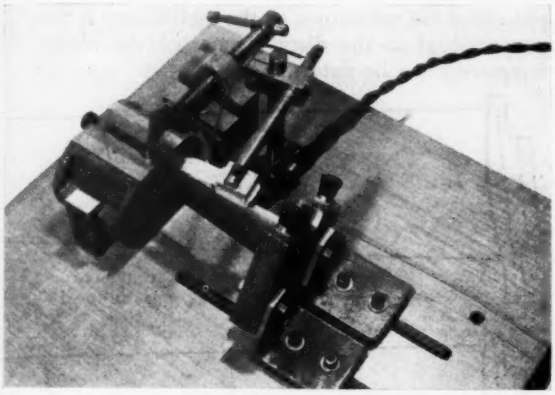

**Figure 7. Mounting of blade and associated components.**

## EXPERIMENTAL PROCEDURE

The original problem, as stated, was to determine the natural modes of vibration of gas turbine blades. This problem can be reduced to two subdivisions; and if accurate information can be obtained about these subdivisions, the solution can be evaluated. (2)

The first part of the problem is the determination of the natural frequency of each mode and the identification of the mode. (8) This, of course, means finding the principal and higher modes of the transverse and torsional vibrations.

The second part of the problem is the determination of nodal patterns present on the blade while it is vibrating in a natural mode. Normally, this vibration is of the traveling wave type, but becomes a standing wave when the blade vibrates in one of its natural modes. This means that the nodes or more specifically the nodal lines are fixed physically. All these nodal lines considered together comprise the nodal pattern of the particular mode. (9)

From this brief discussion of the problem and the description of the operation of the system given in the section entitled, "Design of the System," it can be concluded that a direct method is available for determining the first part of the problem. As previously stated, the displacements increase as a natural mode is approached. Also, the amplitude of the wave form on the oscilliscope is proportional to the displacement. Thus, as the frequency of the driving force is varied, the wave form on the oscilliscope will reach a maximum as a natural mode is approached.

The actual numerical value of the frequency at which the blade is vibrating can be determined by either of two methods. These are first, by doubling the frequency on the audio oscillator dial, and second, by means of lissajous figures. It was previously found that it is most desirable to use lissajous figures, since distortion is present in the alternating current potential. This distortion, combined with the low damping of the blade, will cause the blade to vibrate in one of its modes when the fundamental of the driving force is set at . . . 3, 2, 1, ½, ⅓ . . ., and so forth, of the frequency of that mode. Table 1, is an example of this characteristic of the system. The blade is a General Motors, Allison Division, part number 8981180B, gas turbine blade.

| Multiple of Natural Frequency | Frequency of Force | Multiple of Natural Frequency | Frequency of Force |
|---|---|---|---|
| Number | Cycles per second | Number | Cycles per second |
| 1/6 | 40.0 | 1 | 240.0 |
| 1/5 | 48.0 | 2 | 480.0 |
| 1/4 | 60.0 | 3 | 720.0 |
| 1/3 | 80.0 | 4 | 960.0 |
| 1/2 | 120.0 | | |

Table 1. The frequencies of the driving force at which the first transverse mode can be excited.

The frequencies of the first several natural transverse and torsional modes for the above mentioned blade are given in Table 2.

| Transverse Mode | | Torsional Mode | |
|---|---|---|---|
| Mode Number | Frequency Cycles per second | Mode Number | Frequency Cycles per second |
| 1 | 240.0 | 1 | 1846.0 |
| 2 | 1060.0 | 2 | 5420.0 |
| 3 | 3390.0 | | |

Table 2. The frequencies of the first few modes.

As stated previously, the second part of the problem is that of determining the nodal patterns. A direct method is not available for determining these. However, a standing wave does exist on the blade. This means that the modes or points of maximum displacement and the nodes or points of no displacement are positioned at particular physical locations on the blade. This allows a probe to be used to determine the location of the nodes. If the probe is placed on the blade at any point that is vibrating, the motion will be highly damped. If, however, the probe is placed at a node, the motion will not be damped, since that particular point is not moving. This characteristic

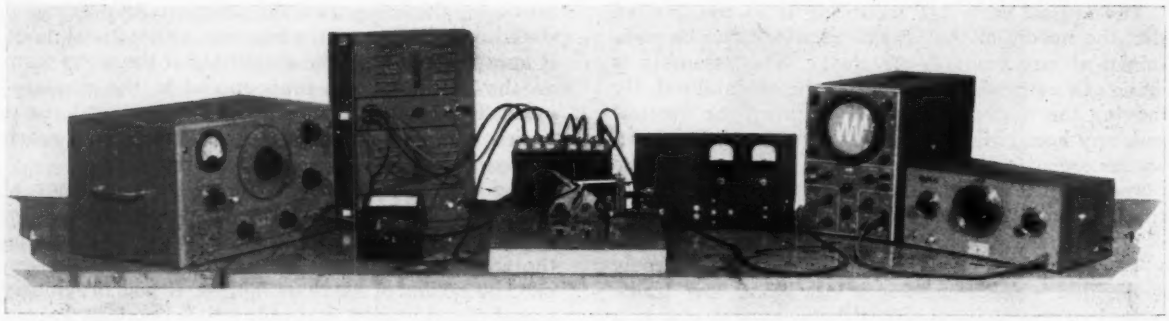

**Figure 8. Laboratory Model**

makes it possible to trace the pattern of the nodes present on the blade. (1)

Figure 9. shows the nodal patterns for the previously mentioned gas-turbine blade vibrating in its second and third transverse and first and second torsional modes. It is of interest to note that the nodal lines are not straight and transverse. This condition is due to the fact that the blade is twisted. The angle of twist for this particular blade is thirty-five degrees clockwise from the base to the free end.

Of course, the determination of the resonant frequencies and the nodal patterns is by no means a complete solution to the vibration problem. If a complete solution is desired, many other characteristics, such as the damping and the effect of the degree of clamping, (10) would have to be studied. This paper, however, is concerned with the design of the system rather than the study of the vibration problem. Therefore, further study of the vibration will not be discussed here.

## SUMMARY

The electrostatic method of excitation described in this report is based on the fact that an alternating current potential impressed across a blade and a block gives a force:

$$F=\frac{\varepsilon_0 A V_m^2}{4D^2} - \frac{\varepsilon_0 A V_m^2}{4D^2}\sin(2\omega t-\frac{\pi}{2}) \qquad (10)$$

The constant term in this expression is equalized by a force obtained from a direct current potential. This leaves a resultant force:

$$F= - \frac{\varepsilon_0 A V_m^2}{4D^2}\sin(2\omega t-\frac{\pi}{2}) \qquad (11)$$

Since the block is rigidly mounted, the force causes the blade to vibrate. A needle from a crystal phonograph cartridge follows the motion of the blade, and causes an electrical potential to be generated. This potential is transmitted by means of a pair of coaxial lines to an oscilliscope, which traces it as a function of time. The resulting figure is proportional to the vibrational displacements as a function of time.

Two experimental methods have been described for using the system to obtain information necessary to determine the natural modes of vibration. The problem has been reduced to two parts: first, finding the frequency at which the natural modes occur; and second, obtaining sufficient data to plot the nodal patterns.

A consideration of the operation of the system gives a solution to the first part of this problem. Since the displacement of the blade is greatest while the blade is vibrating in one of its natural modes and the amplitude of the wave form on the oscilliscope is directly proportional to the displacement of the blade, the frequency can be determined.

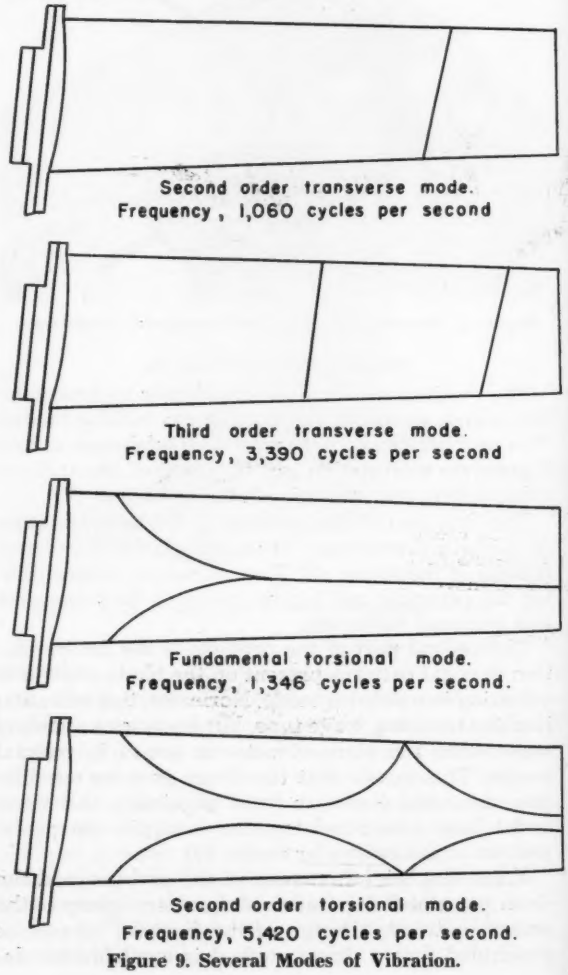
Second order transverse mode.
Frequency, 1,060 cycles per second
Third order transverse mode.
Frequency, 3,390 cycles per second
Fundamental torsional mode.
Frequency, 1,346 cycles per second.
Second order torsional mode.
Frequency, 5,420 cycles per second.

**Figure 9. Several Modes of Vibration.**

The nodal patterns, although they cannot be found directly from the wave converter, are easy to find. A probe is placed on the blade at different points. When the blade is vibrating in one of its natural modes, a standing wave is present; consequently the motion of the blade will be damped unless the probe is placed on a node. This allows nodal lines to be determined, and the nodal pattern ascertained for a particular mode.

Undoubtedly, the system described in this paper is very crude, since it is one of the first of the electrostatic type. It has certain limitations, such as a limited frequency response and a small percentage of distortion in the driving force. Development, however, can overcome these limitations to some extent and greatly extend the usefulness of the system. The theory and a working model have been presented in this paper. Further application and development can progress from this starting point.

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# *DANGERS AHEAD . . . FOR THE ENGINEERING PROFESSION*

**ACKNOWLEDGEMENT**

*This article, appearing in the November, 1955, edition of "Mechanical Engineering," was written by N. T. Veatch, of Black and Veatch, Consulting Engineers, Kansas City, Missouri.*

WHILE EVERY ENGINEER, regardless of where he is, or what he is doing, should be interested in anything that will add to the prestige of the profession, the following statements are directed primarily to members of national engineering societies engaged in the practice of consulting engineering. The number of members of the several societies employed in consulting work represents a large segment of the total membership of such societies. Also this group has perhaps a greater obligation to the profession than any other, as the perfection of its accomplishments and its adherence to ethics of practice are constantly under the scrutiny of the general public.

Those engaged in consulting practice consist of members of many different organizations varying in size from the individual consultant with few if any associates, to large firms equipped to handle projects of any magnitude and complexity. There are firms of all sizes specializing in many divergent lines, such as mechanical, electrical, and hydraulic engineering. There are also many large organizations qualified to handle all phases of large projects. These latter firms usually have been developed over a long period of time and include experts in all the major branches of engineering. Among all of the aforementioned types of consultants there is a difference in age and experience of the members of the organization. With all of the many groups both large and small, and of varied training and experience, that are covering the myriad special lines of engineering work, it is to be expected that the degree of perfection, so far as final results are concerned, will vary. After all, it is impossible to get away from the fact that good engineering is the product of man's brain, either individual or collective, and there is no common yardstick to apply to such service. The real measure of service lies in the production of final results in the most efficient and economical way.

Anyone engaged in engineering work can do many things to enhance the standing of the profession in the minds of the lay public. Undoubtedly one of the best means of doing this is by rendering better and more efficient service. It is believed, however, that there are a few aspects of professional conduct within the profession itself that present a real threat to it, and the correction of these faults will go a long way toward enhancing the standing of the profession.

The question of proper professional conduct within the field of engineering practice is receiving a great deal of study by many of the leading engineering societies. It is well that this is so since the accelerated tempo of the current economy has engendered many new organizations dealing wholly or in part with engineering matters as well as many which offer various combinations of engineering service, contracting, and manufacturing. The very nature of the activities of many of the new firms, as well as that of some of the older ones, has placed emphasis on the commercial rather than the professional viewpoint and it is at least conceivable that this situation, if not controlled, may force the public to consider engineering as a commercial activity rather than a profession. The architects have given this subject a great deal of attention and in many respects they are ahead of the engineers.

The time has come when it is necessary for those of us engaged in the practice of engineering to decide whether we are members of a profession and to act

accordingly, or whether our activities are commercial and to govern ourselves by commercial standards. Only those within the profession itself will or can do anything about the situation, and since the only bodies that are in a position to speak for the profession are our engineering societies, the danger of making a wrong decision is a definite challenge to these societies.

While the engineering profession is actually very old, it has been recognized as a truly learned profession for only a little over a century. Comparatively speaking, it is the youngster of the accepted professions but it has earned a status of which we are justifiably proud. This status is the result of long and conscientious effort on the part of many fine individuals. It would be a shame to allow unprofessional practices which detract from the high standing of the profession to continue with anything that even gives the appearance of consent.

The following subjects are believed to justify special attention from the national societies because, if not properly controlled, they will certainly undermine the profession.

1. *Competitive Bidding for Professional Engagements.* Instances of competitive bidding for professional services seem to be increasing in number. There are cases where bids are actually requested as well as submitted by members of the leading engineering societies and under circumstances which indicate clearly that price is the controlling consideration.

2. *Advertising.* The use of display and sometimes self-laudatory advertising on the part of members of the profession are also becoming more prevalent. Most of these cases involve those who offer a combination of engineering service with construction or manufacturing.

3. *Engineering by Contractors and Manufacturers.* Engineers employed by contractors and manufacturers have made outstanding contributions to society and to the profession. Everyone should be grateful for this contribution. However, there are quite a few cases where a contractor is given a contract under which engineering is also furnished. The circumstances surrounding such arrangements determine whether such a plan is to the best interests of the client. Also, there is a practice among some of those engaged in the consulting field to allow contractors and manufacturers to do engineering work which they, the consultants, should do themselves and by so doing have often brought about improper and expensive design.

The foregoing list is by no means complete but most of the transgressions in question seem to fall into one of the three categories. In this discussion, fraud and other crimes under civil law have not been considered.

### COMPETITIVE BIDDING

Competitive bidding is believed to present one of the gravest dangers to the engineering profession. Its universal adoption on the part of the engineer and the client would end any justification for engineering being considered a profession.

Competitive bidding is well established as a proper and many times a desirable practice in commercial-business transactions. It has not been a serious problem in any of the other learned professions due to discipline within their own ranks. It has become a real problem in engineering perhaps because the engineer is usually directly concerned with projects involving competitive bidding and the expenditure of large sums of money.

Engineering is the most essential component of every item of construction or manufacture, be it a sidewalk or a battleship, and since competitive bidding is adaptable to most of the other components, it requires some careful thinking to realize that the temptation to include engineering service in a bid is actually not to the best interests of the owner or client.

It is believed that competitive bidding may be properly used for anything that may be adequately specified, but no one can adequately specify the workings of a man's brain. That is exactly what is involved in engineering service. If there is any single lesson to be learned from centuries of professional experience it is that brain power cannot be and should not be standardized.

There are many circumstances presented to the practicing engineer in the requests received for information regarding his services. The requests range from a statement that bids, sometimes designated as sealed bids, will be received at a certain date and time and then publicly opened, to one which states the engineer has been selected to perform certain services and asks for a formal proposal. At times there is even a formal advertisement for bids. Requests for competitive bids on a price basis whether by letter or through a formal advertisement or the submission of a proposal in response to them would be clearly an infringement of the codes of the leading engineering societies.

There are other circumstances where the proper procedure is not so clearly defined. It is believed that from a practical standpoint, a prospective client can very properly consider the amount of fee to be paid, as well as the qualifications of the engineer. The real purpose of the several codes is to require members to adhere to practical professional standards in connection with the engagement of engineering services. Manifestly the selection of an engineer for any particular task should not be based solely upon his fee, as the interest of the client lies in the total cost of the project rather than the cost of engineering. This is the main reason the societies have in their codes of ethics an article prohibiting competitive bidding, for often, if not generally, employment of an engineer with less experience and with the lowest fee will result in either a higher total cost or an inadequate design.

It must be recognized that there will constantly be new faces appearing in the consulting field, and such individuals or firms must get a start, and that only

time and experience can make their services comparable to those of older ones. Naturally, these younger consultants will and can furnish services for lower fees than those having more expensive operations. These newer firms or individuals have a very proper place in the profession as they will someday be the leaders and there are many projects upon which their services are entirely satisfactory. However, the clients' interests will always be best served if selection of engineering talent be governed primarily by qualifications needed for the particular project and with the fee being entirely secondary.

It is believed that all of the practical requirements of the prospective client can be met and at the same time meet the full intent of the several codes. There is no reason why an engineer cannot discuss his fee with a prospective client whenever he is asked to do so. The only prohibition to his doing so is that he does not submit a fee when he knows that it will be solely controlling in the selection. It is also believed that each engineer will always know what the circumstances are in connection with any particular project on which he is either asking for consideration or where he is responding to some form of request. It would certainly be proper for an engineer to state his fee for his engineering services during negotiations after he has been selected by the client on the basis of his professional qualifications and ability to perform the services.

A recent instance of competitive bidding is worth citing as it resulted in the expulsion of one member of the American Society of Civil Engineers and suspension of membership of others.

Late in 1953, the State Highway Commission of South Carolina found itself with more work than could be handled by its own engineering department and decided to employ an engineering firm to prepare plans and specifications for certain structures. Bids from engineers were requested by advertisement in the manner customarily used for obtaining bids from contractors. Fifteen engineering organizations responded. The "bids" ranged from 2.8 to 7.25 per cent of the contract cost of the work and the contract was awarded to the lowest bidder.

It is difficult to believe that either the services contemplated by all of the "bidders" were identical or that all of the "bidders" were equally competent. "Plans and Specifications" for a *bridge* were specified but the essential matters of quality of plans and competence of engineers were not. It seems probable that the client not only paid the lowest fee but also may not have got the best in service. In this instance, the interests of the client and the public as well as those of the engineer were involved and the unmistakable lesson it teaches is that competitive bidding failed to serve any of these interests whereas compliance with proper ethics would have served all of them.

#### COMPETITIVE BIDS REQUIRED BY LAW

It is very common to find provisions in state laws or city ordinances to the effect that every contract which involves more than a certain sum of money shall be awarded to the lowest bidder after public advertisement and such provisions have been cited as a reason for compelling competitive bidding for professional services. Fortunately this is not the case. The courts, through a large number of decisions, have held that provisions as to competitive bidding do not apply to contracts for personal services which depend upon the particular skill of the individual, such as the services of an attorney at law, a superintendent or architect, or a consulting and supervising engineer, and generally that the provisions do not apply to the employment of a professional man, in which case the authorities have a discretion as to his qualifications.

The language of some of the decisions is enlightening. The Supreme Court of Colorado in a decision involving the employment of an architect stated: "We now say that anything said in those cases that may be construed to be a holding that the charter provision is applicable to a contract for architectural services is overruled, and we accept with complete approval decisions of other jurisdictions, including California, Indiana, Massachusetts, Minnesota, New York, North Dakota, Ohio, Pennsylvania, and Texas, holding that a municipality can contract for the services of an architect without complying with such a requirement as is contained in the charter section in the present case."

"We are satisfied to accept and adopt the following language . . . The value of such service is not to be measured by a mere matching of dollars, so to speak; it is not to be determined upon the irrational assumption that all men in the particular class are equally endowed with technical or professional skill, knowledge, training, and efficiency. Nor are such services rendered more desirable because offered more cheaply in a competitive bidding contract. The selection of a person to perform services requiring those attributes calls for the exercise of a wise and unhampered discretion in one seeking such services, for it involves (not only) personal and professional trustworthiness but responsibility as well."

The virtually unanimous action of the courts on this subject constitutes recognition of the professional status of engineering from a most reliable source. Competitive bidding is demonstrably unnecessary, unreliable, and unsatisfactory and we are deeply indebted to our engineering societies for declaring it contrary to proper ethics.

#### ADVERTISING

Advertising has been a ticklish subject in professional circles for many years. The general concensus seems to be that, where such services are involved, advertising should be limited to a professional card which states that the individual (or firm) is practicing a certain profession at a certain address.

The Code of Ethics of the American Society of Civil Engineers (Article 7) states that it shall be considered unprofessional and inconsistent with honorable and dignified bearing for any member: "To advertise in self-laudatory language or in any other

manner derogatory to the dignity of the profession."

Other societies have similar code provisions and it is clear that in the minds of these leaders of the profession, advertising, in the usual sense of the term, is not ethical.

The Committee on Professional Practice of the American Society of Civil Engineers has commented as follows in the attempt to clarify the situation. Within the meaning of the Code, the Committee is of the opinion that:

"Engineering firms and individuals offering professional services to the public may properly advertise such services by procuring the publication of a professional card in any magazine of technical or professional character having a section specifically designated as a professional directory. Such professional cards shall include *only* the name and business address of the firm or individual, the names of key personnel, and the scope of the services offered. The size and form of such professional cards shall be such as to avoid undue display and shall be in general conformance with such cards appearing in the Professional Directory of *Civil Engineering*, an official publication of the American Society of Civil Engineers."

"Such professional cards may not properly be displayed in any newspaper, nor in magazines of nontechnical or nonprofessional character, nor in any publication which does not regularly carry a classified section specifically designated as relating to the practice of professional engineering."

"Engineering firms and individuals offering professional services to the public may properly distribute to prospective clients brochures or booklets, containing a list of completed professional engagements, descriptions of all services offered, factual statements of accomplishments and qualifications of key personnel, and descriptions, photographs, and/or other illustrations of works upon which their professional services have been employed. Such brochures or booklets may not properly include the advertisement of any commercial product or equipment, nor any self-laudatory statements. They shall be in all respects of a character tending to uphold the dignity of the profession."

"Engineering firms or corporations offering, in addition to professional engineering services, such other services as construction, management, financing, and personnel employment, may, under similar restrictions as to content, distribute brochures or booklets, covering all services offered, including professional engineering services. They may not, however, advertise the essential combination of professional engineering services with other services either in such brochures or booklets, or in any display advertisement in a publication of general circulation, nor by direct statement or implication combine an offer of professional engineering services with an offer for such other services."

It would seem that there should be little chance of misunderstanding the spirit of this section of the Code. Essentially it is the dignity of the profession that is at stake and common prudence suggests that the proper course of action lies in the "avoidance of the appearance of evil."

It is difficult to conceive of a situation in which the return from an unrestricted advertising program to an individual engineer or firms of engineers would be sufficient to compensate for the sacrifice of professional standing, but even if the return should appear adequate to the individual the societies should maintain the right to disciplinary action in case a member is involved.

#### ENGINEERING BY CONTRACTORS AND MANUFACTURERS

From the ethical standpoint matters get quite involved when engineering service is combined with construction.

It has been said that "one cannot umpire and play in the same ball game" and the logic of this philosophy must be admitted. So it seems that the criterion, when engineering service is concerned, is whether the engineer is offering his services as an "umpire" or as a "player." This foregoing statement stretches the metaphor a little but is intended to differentiate services as a representative of the client from those as a representative of the contractor.

It is conceivable that the owner may be an engineer or have regular employees who are competent to judge engineering and desire to have the project designed and constructed under a single contract. Such arrangements are in fact common in industrial work. Engineering organizations considered are carefully screened prior to the negotiation of a contract and finally the functions of the engineer so far as ethics is concerned are performed by the owner or his employees. In other words, an umpire may not be needed.

If, on the other hand, the owner is not prepared to do his own engineering and is in need of such services he must look to the profession and the matter of ethics is most important. His game needs an umpire and one who is above any suspicion of bias. He cannot afford to take chances and it is with the interest of clients of this type in mind that the societies have incorporated provisions of the following nature in their codes of ethics.

"It shall be considered unprofessional, etc., to act for his clients or for his employers in professional matters otherwise than as a faithful agent or trustee, or to accept any remuneration other than his stated charges for services rendered his clients."

Some manufacturers of various types of equipment will, on request, provide engineering services in connection with plant design and some consulting engineers will incorporate the results of such engineering work in the plans furnished the client. This situation abounds in "borderline" cases so far as ethics is concerned but the main point is that a client has the right to expect the consulting engineer to perform services himself and not to delegate his responsibility. The fault seems to be divided between the manufacturer and the engineer, but from the standpoint of ethics the responsibility must lie with the engineer who permits such procedure.

### REMEDIAL MEASURES

Two facts seem to be quite clear:

1. Indifference to code violation on the part of the profession itself is certain to be construed by the public as acceptance on the part of the engineers.

2. Any remedial action to be effective must be taken by the societies for the reason that only they are in a position to speak for the profession and to impose disciplinary action.

A third and rather obvious fact, so far as the public is concerned, is that action by all of the societies must be along parallel lines and the similar nature of the ethical codes of the several societies gives assurance of the possibility of such action.

It is wishful thinking to believe that dangerous practices can or will be entirely eliminated by any action on the part of the profession. Centuries of legislation have failed to stop crime but have made it very unpopular and it seems probable that appropriate action by the societies can reduce greatly the number of code violations.

It should be remembered that every society member has subscribed to a code of ethics and that in the final analysis no member need be asked to do anything that he has not already promised to do in order to follow the code.

The real problem is, has been, and will be, the interpretation of the several codes and this means work for our Committees on Professional Practice. Each actual or alleged violation must be considered on its individual merits by competent persons and it is the spirit rather than the language of the code provisions that must be upheld.

Some of our codes have been criticized as being too harsh and in not a few cases changes have been suggested, but generally the spirit has not been questioned. We must be ever on the alert lest by trying to improve our codes we open up additional loopholes for use by those who desire them. "Thou shalt not steal" seems rather short and abrupt if not actually harsh, but no one has attempted to challenge its meaning. It certainly would not be helpful for this commandment to be amended to read: Thou shalt not steal except under the following circumstances, etc.

Our societies probably cannot stop all code violations but they can maintain discipline among their members and when this is accomplished the profession will be in a vastly improved condition. We can bring this about but we must keep "on our toes" to do it.

LYNDON CRAWFORD

# *PIPING UNDER DYNAMIC LOADING*

**THE AUTHOR**

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## I INTRODUCTION

Some ships' piping systems have become dominant equipment items in the same sense as are pumps, heat exchangers, and the like. Durability of piping perhaps has taken on greater significance in recent years. The security of radioactive coolant loops is, of course, a case in point.

There is a substantial volume of literature on static properties of general piping systems. This work has been primarily tailored to the needs of thermal stress calculations. The influence of external loads, other than those of the anchors, and of body loads has not frequently been discussed. This has been particularly true of dynamic loads on piping systems except for long straight runs.

There is good reason for this. Thermal stresses are the most obviously important in a majority of cases. And piping often constitutes a most difficult class of space framework to analyse. Numerical barriers to general solutions are quite formidable; in fact, while hand solutions of thermal problems are relatively common, the advent of automatic computing machines has provided a great encouragement to more rigorous thermal analysis. In the case of dynamic analysis it is only the existence of automatic computation which can justify the attack.

As it is, it is probable that dynamic analyses would be confined for some time to come only to the most vital of shipboard piping. Piping, of course, has often been situated in a vibrational environment and has been stressed therefrom. And under shock dynamic loads can be most severe. Under steady state operating conditions a severe resonant vibration of piping can be detected if the systems are visually accessible. Hangers can be fitted to break this up. But, of course, the actual stresses remain unknown. And if the piping cannot be seen during operation, even the resonance cannot be detected. To be sure, it is possible to test for resonant frequencies prior to service with small vibration generators or even by striking the pipe system and checking for various natural harmonic frequencies. And there are doubtless many cases where this is the more propitious action. Model testing for natural frequencies is entirely possible but suffers from problems of scale effects, the duplication of end conditions and the like. The determination of natural frequencies does not completely 'solve' the vibration problem. It does not predict stress levels, nor does it give indication on what excursions the pipe may take in service.

The likelihood of failure of piping under dynamic loading may be rather remote, but there are certain cases where the effect of failure would be grave in the extreme. It is to these cases that this paper is addressed.

The purpose here is to demonstrate that classical principles can be applied to this class of problem with terminal results that are not at all unlike those which are found elsewhere in applied mechanics and which are usually reserved for structures whose motion is primarily uniaxial. Blake and Swick (2) have recently offered an excellent demonstration of uniaxial motion. In this paper on space problems the reader will note strong similarities here to that work. It is demonstrated here again that once the static

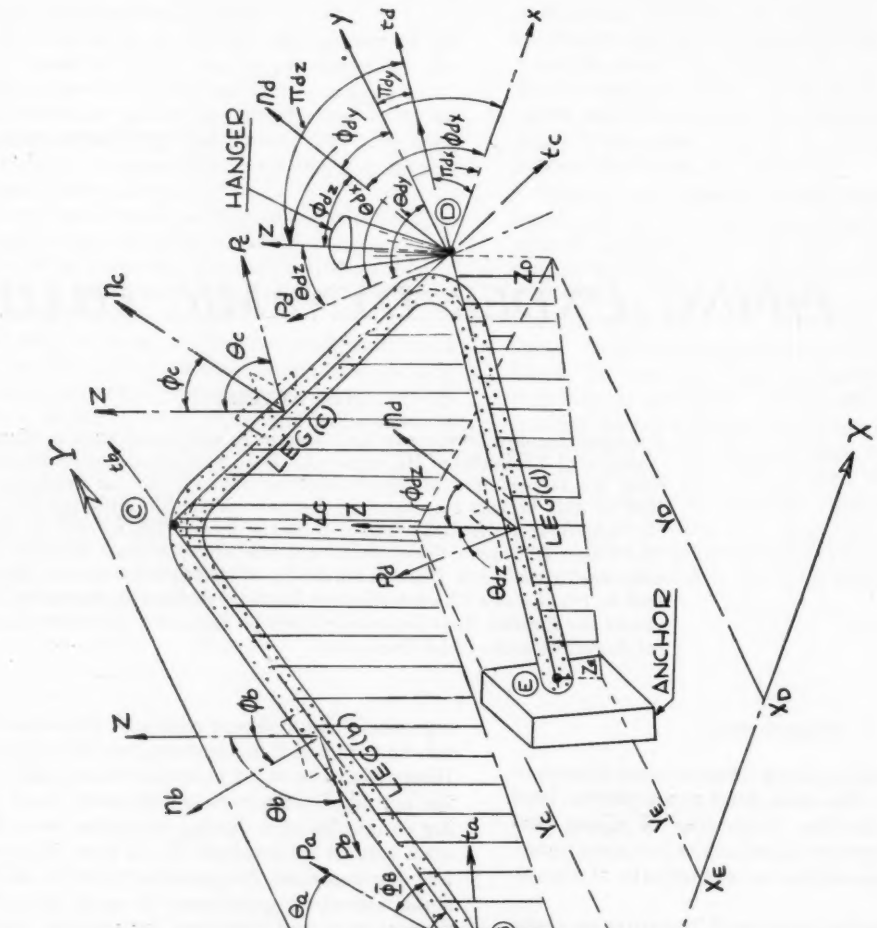


FIG. 1 ILLUSTRATIVE PIPE RUN

properties (in the form of influence coefficients) have been established and the dynamic properties (in the form of natural frequencies and normal modes), we are quite close to solution providing that the exciting stimuli and the damping properties can be defined. In the case of shock the latter consideration takes on less importance. The example of a single specific pipe run is used. Some notes on partially plastic action of piping are appended.

## II STATIC-ELASTIC PROPERTIES

Figure (1) shows a pipe run in space that can illustrate most of the principles that are brought out here and which are in general, also applicable to branched piping. Notes on the effects of partial constraint by hangers or anchors, and on the effects of long radius or compound bends appear at a later point to indicate fairly minor variations on the main theme. The illustrative pipe ABCDE is, thus, an unbranched (two-anchor) system with a rigid pipe hanger at D‡. The supports, A and E, could be taken as pumps, heat exchanger, boilers or the like, and at these points the pipe is considered completely constrained against flexural and torsional rotations as well as against displacement in any direction, under the influence of any load on the run. At D the hanger constrains the pipe against displacement in any direction but permits freedom of rotation about any axis again with applied loads on the pipe run. (Actually the sharp corners, B, C, and D are the intercepts of the adjacent straight axes of the run.)

For the sake of convenience orthogonal coordinate systems, n, p and t, are assigned to each straight leg of the run.

It will be seen that between A and D this pipe is free to sway elastically with motion parallel to the leg 'b'.

In the ordinary static problem we are usually interested in maximum flexural, axial and torsional stresses and occasionally in deflections at representative points. It is customary, and in many cases doubtless more economical, to treat such problems 'as a whole.' Either all the external loads are treated at once, or a combination of the thermal movements of the terminals together with the pipe (metal) temperature is given, and the combination is solved as a piece.

For dynamic analysis we need to understand the static properties in greater breakdown. The method chosen here commences with the selection of 'n' points along the pipe run at which the local mass of the pipe can be considered concentrated. These points will include any actual locations of concentrated mass and also the corner points B, C and D. And for these points we require influence coefficients defined as deflections caused at the various mass points by unit forces applied singly at the various mass points. In a space frame such as this, any deflection is a vector quantity, and therefore we deal in components. For example, we can define:

$\alpha_{kj}$ Defl'n at $m_k$ in $n_k$* dir'n due to unit force in $n_j$* dir'n at $m_j$
$\bar{\alpha}_{kj}$ Defl'n at $m_k$ in $n_k$ dir'n due to unit force in $p_j$ dir'n at $m_j$
$\beta_{kj}$ Defl'n at $m_k$ in $p_k$ dir'n due to unit force in $n_j$ dir'n at $m_j$
$\bar{\beta}_{kj}$ Defl'n at $m_k$ in $p_k$ dir'n due to unit force in $p_j$ dir'n at $m_j$

$m_k$ and $m_j$ are arbitrary mass joints. Maxwell's reciprocal law† implies here:

(1) $\alpha_{kj}=\alpha_{jk}$; $\bar{\alpha}_{kj}=\beta_{jk}$; $\beta_{kj}=\bar{\alpha}_{jk}$; $\bar{\beta}_{kj}=\bar{\beta}_{jk}$.

Thus the major determination resolves itself into a series of static problems of the type shown in Figure (2) where a unit force in the 'p' direction, for example, at the arbitrary point $m_j$, is applied. The 'n' and 'p' component deflections for such a load application are desired for all mass points including $m_j$. Any tangential deflections in leg 'b' are reflected in the $n_a$ and $p_a$ directions at the corner B. Figure (3) illustrates the same problem where the anchor, E, and the hanger, D, have been removed, but the forces and moments which they would exert are shown under the same load application ($F_j$=1.0) resolved into the convenient components $M_{nE}$, $M_{tE}$ etc. These forces and moments (redundants) are not known, but if they were the problem would thence be statically determinate with six equations of statics to determine the three moment components and three force components at A. We could also by pure static considerations determine all the deflection components at any point, and that is what this sub-problem is about. The job is to determine the nine unknowns, $M_{TE}$, $M_{nE}$, $M_{PE}$, $N_E$, $P_E$, $T_E$, $R_{nD}$, $R_{pD}$, $R_{tD}$ for any $F_j$ load individually.

Under the circumstances we can write expressions for the forces and moments acting on any small element of the run, ds, as shown in the enlarged cut on Figure (3) from statics and the geometrical features of the run. These expressions will contain the unknown redundants. We are in general only to be concerned with flexural and torsional strain energy and will ignore generally that due to axial forces.** The total strain energy will naturally be expressible:

$$(2)\quad V=\int_{Run}\frac{M_f^2 ds}{2\cdot k\cdot E\cdot I_x}+\int_{Run}\frac{M_t^2 ds}{2\cdot GI_P}$$

‡While 'D' is an intercept of the axes of two legs and not actually a point on the run, the principles brought out here are unaltered for any location of a hanger.

*The subscripts for 'n' and 'p' refer to the local reference axes of the pipe leg in which $m_k$ or $m_j$ is situated.

†The general proof of Maxwell's basic law can be found in many standard references, (21) for example. The above follows directly for space frames.

**We have an exception: see page 348.

$M_t$, $M_f$—Torsional and flexural moments at the arbitrary section, ds.
where:

$k=1.0$ if ds is in a straight section of pipe

$k=1.0-\dfrac{9}{10+12\left(\dfrac{tR}{r^2}\right)^2}$ if ds is in a bend*—(Karman correction factor)

| | |
|---|---|
| R | centerline radius of pipe bend |
| r | mean radius of pipe material |
| $I_X$, $I_P$ | flexural and polar moments of inertia of pipe section |
| E, G | tensile and shear moduli |

The principal conditions of this problem are that there shall be no elastic displacements at E and D nor any elastic rotations at E. This is expressible using our energy relationships and the second theorem of Castigliano thus:

$$(3)\quad \begin{cases} \dfrac{\partial V}{\partial M_{tE}}=0;\ \dfrac{\partial V}{\partial M_{nE}}=0;\ \dfrac{\partial V}{\partial M_{pE}}=0. \\ \dfrac{\partial V}{\partial N_E}=0;\ \dfrac{\partial V}{\partial P_E}=0;\ \dfrac{\partial V}{\partial T_E}=0. \\ \dfrac{\partial V}{\partial R_{nD}}=0;\ \dfrac{\partial V}{\partial R_{tD}}=0;\ \dfrac{\partial V}{\partial R_{pD}}=0. \end{cases}$$

It is clear from (2) that the strain energy can be expressed as a function of the nine redundants; a brief examination shows that the above relationships (3) will yield nine equations linear in these same redundants and solvable for same. With this solution the properties that we desire are in our hands.

The above, of course, illustrates nothing more than a familiar idea in the treatment of pipes and frames. The precise methodology may follow somewhat modified form depending on computation ease.

The immediate reaction to all of this so far must be that since we have quite a number of these problems —one for each unit force application in two directions—then our numerical prospects are quite overwhelming. And so it would be, were it not for the availability of automatic computation. Actually the shift of the point of force application or a directional shift of same only changes the constant terms resulting from equation (3). From a computation point of view this is significant, as it suggests that the overall program for determination of all influence coefficients could be given to a machine at one time; this is a matter of memory capacity of the machine being used. In shifting from one pipe run to another, much of the basic program can be retained providing that there has been some standardizing on the number of mass points. For example, it would be quite possible to arrange a general program for a single branched pipe run with three anchors but without hanger(s) which could cover a very large number of real cases. The subsequent inclusion of hanger effect should pose few problems other than the inclusion of fairly simple subroutines; instructions for use would be included when the specific data input would be supplied.

In fact, because we are going to be interested in certain dynamic properties of this pipe run, it is worthwhile to point out an alternative treatment. The pipe run could be reduced at the start by the removal of the intermediate hanger at D as shown on Figure (4). We could now examine the behavior of this reduced pipe run under the application of the same unit forces separately including unit forces in $n_d$, $p_d$ and $t_d$ directions at D. The figure shows the application of a forme, $F_{tD}=1.0$, in the $t_d$ direction at D. This particular force application implies stretch in the leg, d, and we will not be grossly inconsistent if we ignore elastic stretch in the other legs for this force application.‡

Under such a load the reduced pipe run would deflect as shown AB′C′D′E in the figure with parallel sway in both legs b and c. We will designate all influence coefficients of the reduced run with primes and can define the following additional coefficients:

$\alpha'_{kD}$ Defl'n in the $n_k$ dir'n at $m_k$ due to unit force in the $t_D$ dir'n at D
$\beta'_{kD}$ Defl'n in the $P_k$ dir'n at $m_k$ due to unit force in the $t_D$ dir'n at D

The solution of influence coefficients would be very similar to that of the original problem except that, with the hanger removed, there are but six redundants, three moments and the three reaction forces at E. To include the strain energy of axial forces in leg d only we write for strain energy:

$$(2A)\quad V=\int_{\text{Run}}\frac{M_F{}^2ds}{2kEI_X}+\int_{\text{Run}}\frac{M_T{}^2ds}{2GI_P}+\int_{\substack{\text{Leg d}\\ \text{Only}}}\frac{F'_d{}^2ds}{2A_PE}$$

where $A_P$— cross sectional, metal area of the pipe. The application of the second theorem of Castigliano in this case would breed six simultaneous equations in the redundants. The new influence coefficients would thence be solvable through statics. They would not be the correct coefficients for the real problem, but they could be used for same provided that we had defined and similarly solved for the special influence coefficients:

*See reference (20) page 110.

‡This is brought out in anticipation of relative shock excursions of the hanger at D which would force axial displacements in this leg which would influence the flexural and torsional action elsewhere.

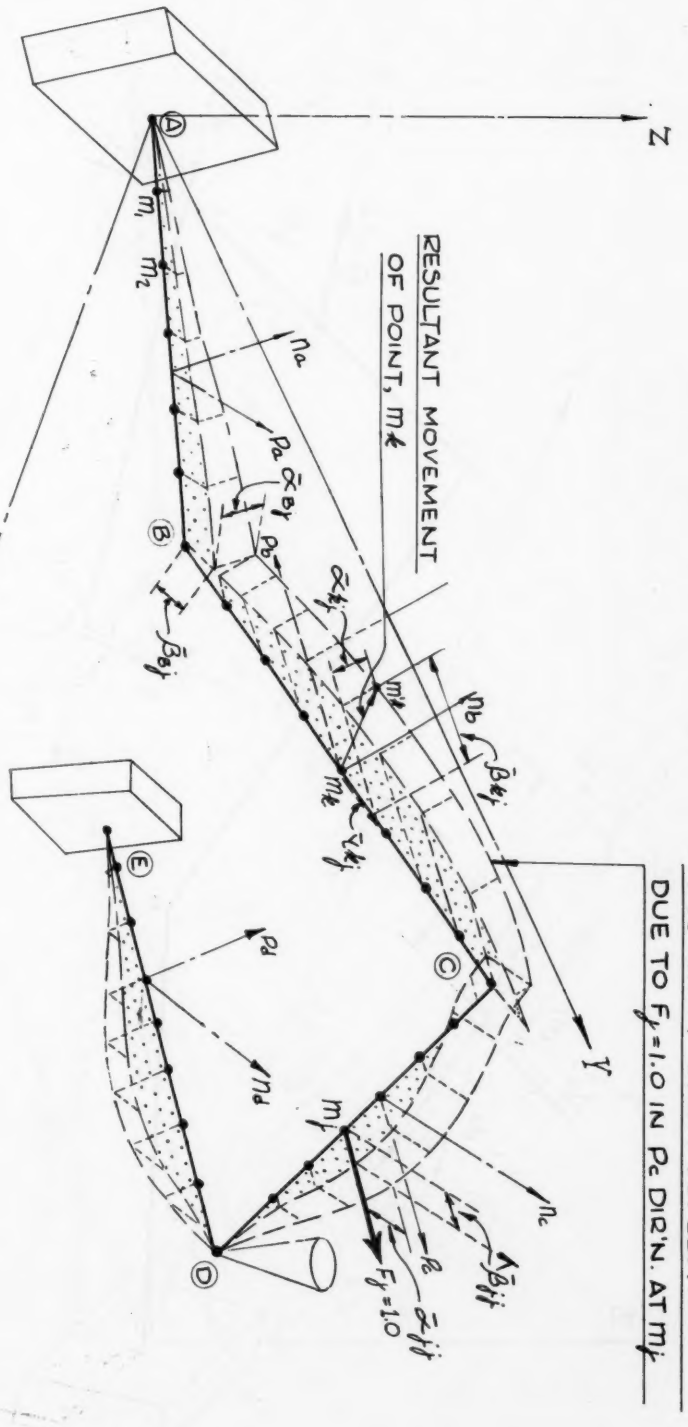


FIG. 2
INFLUENCE COEFFICIENTS

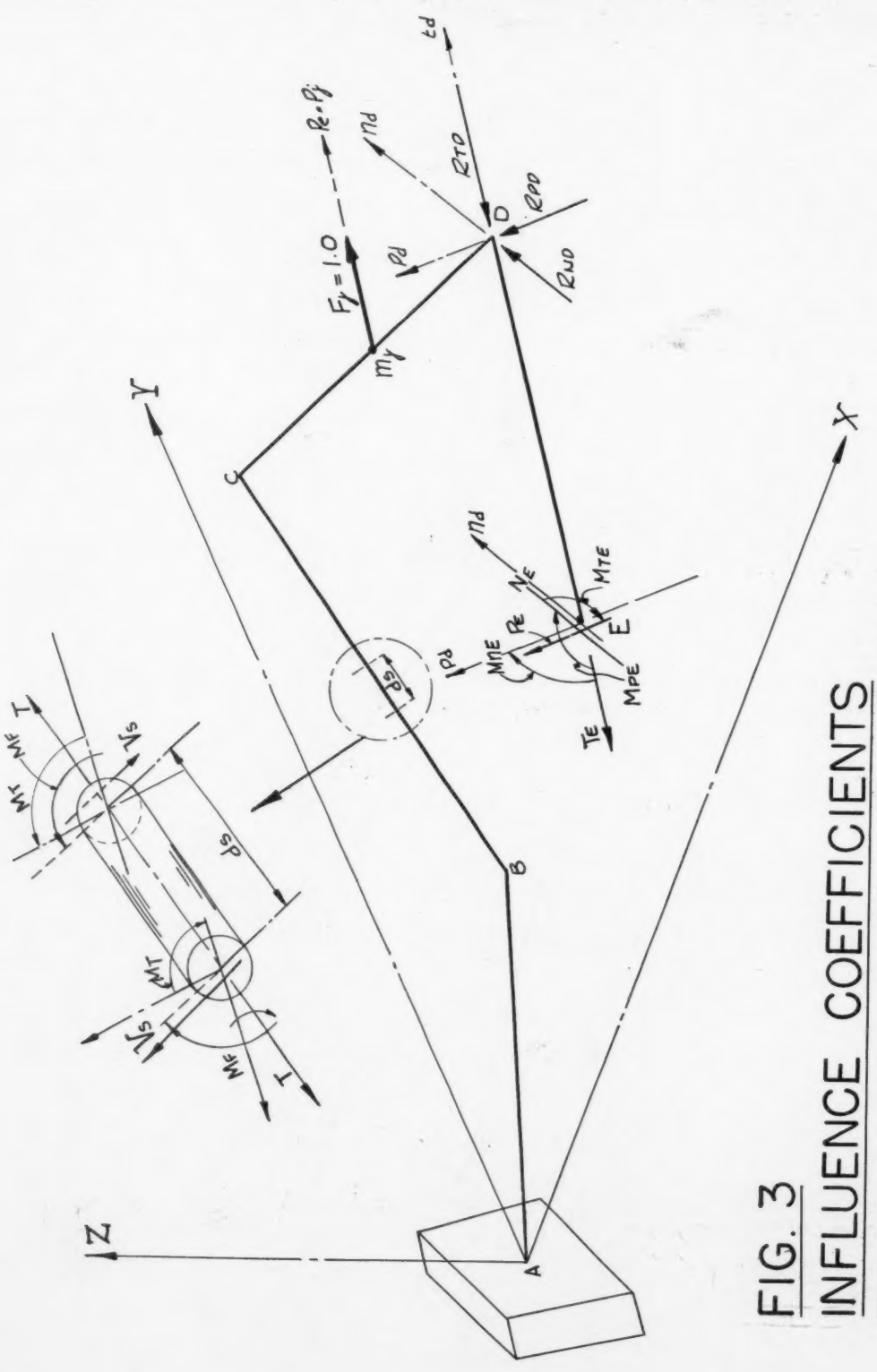
Y
X
Z
A
B
C
D
E
SP
Fy = 1.0
my
Pd
Pd
Pd

FIG. 4
INFLUENCE COEFFICIENTS
OF REDUCED PIPE RUN *

* NOTE:- HANGER AT D HAS BEEN REMOVED.

$\gamma'_{Dj}$ Defl'n in the $t_D$ dir'n at D due to unit force in the $n_j$ dir'n at $m_j$.
$\bar{\gamma}'_{Dj}$ Defl'n in the $t_D$ dir'n at D due to unit force in the $p_j$ dir'n at $m_j$.
$\bar{\bar{\gamma}}'_{Dj}$ Defl'n in the $t_D$ dir'n at D due to unit force in the $t_j$ dir'n at $m_j$.

The reduced pipe run problem can be made equivalent to the original problem if the load, say the original load, $F_j=1.0$ (in the p direction at $m_j$), were to be applied to the reduced pipe run *plus* three orthogonal forces at D, such as to produce no displacement at D. (These are, of course, the original hanger reactions of the original problem, but now the influence coefficients of the reduced run have been calculated.) This condition can be expressed with the new symbols:

$$(4)\quad \begin{cases} 1.0\ \alpha'_{Dj}-R_{tD}\ \alpha'_{DD}+R_{nD}\ \alpha'_{DD}+R_{PD}\ \bar{\alpha}'_{DD}=0 \\ 1.0\ \bar{\beta}'_{Dj}-R_{tD}\ \bar{\beta}'_{DD}+R_{nD}\ \beta'_{DD}+R_{PD}\ \bar{\beta}'_{DD}=0 \\ 1.0\ \bar{\bar{\gamma}}'_{Dj}-R_{tD}\ \bar{\bar{\gamma}}'_{DD}+R_{nD}\ \gamma'_{DD}+R_{PD}\ \bar{\gamma}'_{DD}=0 \end{cases}$$

These equations are simultaneous and solvable for the residual unknowns, $R_{tD}$, $R_{nD}$, and $R_{pD}$. In fact, had there been more hangers, we could have applied them one by one in this way to the reduced pipe run using equations such as (4).

This may seem like a long way around, but the latter could be turned into a standardized subroutine to maintain a generality to a basic computation program. Be this as it may, we can now evaluate the real influence coefficients with equations such as the following:

$$(5)\quad \bar{\alpha}_{kj}=\bar{\alpha}'_{kj}+R_{nD}\,\alpha'_{kD}+R_{pD}\,\bar{\alpha}'_{kD}-R_{tD}\,\bar{\bar{\alpha}}'_{kD}$$

which utilizes the reduced coefficients and the recently solved hanger reactions.

Considering the title of this paper, one might feel that we have been belaboring static problems. But, in common with many dynamic problems, the static properties often procedurally give the greatest labor. If at some later stage we learn to treat partially plastic action, the above observation may lose some force. This paper primarily concerns linear elastic action where we must understand the static properties quite thoroughly.

### III VIBRATION AND NORMAL MODES

Figure (5) illustrates the same pipe run at a moment of maximum excursion when it is vibrating freely at one of its natural frequencies, $\omega_i$. An arbitrary condition has been placed on this particular vibration: the component of the amplitude of the $F_{th}$ mass, $m_F$, in the local n direction has been set equal to unity. This is a process of normalizing which permits comparison between various natural modes of vibration. Thus the illustrated deflected curve, $AB'C'DE$, is taken as the ith normal mode.

The shape of this normal mode is defined by vectors in space defined, $\vec{a}_{ki}$ representing the movements of all mass points, $m_k$. The hanger at D causes that point to be a node of zero movement. It can be demonstrated that any elastic deflection pattern of such a frame (pipe) can be considered to be the sum of a series of curves geometrically similar to its normal mode shapes. The lumping of masses discussed in the previous section changes our model from a real, infinite degree of freedom system to an approximate 2n degree-of-freedom system which requires 2n parameters to define any instantaneous position that it may adopt.

With free vibration, the only forces that cause deflections are inertial. In our lumped mass model these forces occur at the mass points only. For example, when the kth mass is in the leg b its inertial force on the system is a vector, $(\vec{\omega}_i^2\, m_k \vec{a}_{ki})$. Its motion is defined $\vec{a}_{ki} \sin \omega_i t_o$. The vector is built from the coordinate inertial forces, $\vec{\omega}_i^2 \xi_{ki} m_k$, $\vec{\omega}_i^2 \zeta_{ki} m_k$ and $\vec{\omega}_i^2 m_k \kappa_{ki}$ in the $n_b$, $p_b$ and $t_b$ directions respectively.

The sum of all the axial inertial forces in leg b (in the $t_b$ direction) can be lumped and said to apply to the system at the corner point, B, since we are not considering axial-elastic action in the legs. This force can be described:

$$(6)\quad F_B=\vec{\omega}_i^2 M_b \kappa_{Bi}$$

where $M_b$ is the mass of the whole bth leg.

The tangential movement $\kappa_{ki}=\kappa_{Bi}$, is shown on the insert of Figure (5) and can be seen to be directly related to the two components of movement, $\xi_{Bi}$ and $\zeta_{Bi}$, in the $n_a$ and $p_a$ directions at B respectively:

$$(7)\quad \kappa_{ki}=\kappa_{Bi}=(\xi_{Bi}\cos\Psi_B+\zeta_{Bi}\cos\Phi_B).$$

Then the tangential inertial force is expressible:

$$(8)\quad F_B=\omega_i^2 M_b(\xi_{Bi}\cos\Psi_B+\zeta_{Bi}\cos\Phi_B).$$

And this force has components in the $n_a$ and $P_a$ directions:

$$(9)\quad F_{Bn}=\vec{\omega}_i^2 M_b(\xi_{Bi}\cos\Psi_B+\zeta_{Bi}\cos\Phi_B)\cos\Psi_B$$
$$(10)\quad F_{BP}=\vec{\omega}_i^2 M_b(\xi_{Bi}\cos\Psi_B+\zeta_{Bi}\cos\Phi_B)\cos\Phi_B.$$

The point, B, was chosen as one of the lumped mass points with its own inertial forces in the $n_a$ and $p_a$ directions. $\vec{\omega}_i^2 M_b \xi_{Bi}$ and $\vec{\omega}_i^2 M_b \zeta_{Bi}$, respectively. Thus the total forces in the $n_a$ and $p_a$ directions at B are:

$$(11)\quad F_{Bn}=\vec{\omega}_i^2[(M_b\cos^2\Psi_B+m_B)\xi_{Bi}+M_b\cos\Phi_B\cos\Psi_B\cdot\zeta_{Bi}]$$
$$(12)\quad F_{BP}=\vec{\omega}_i^2[(M_b\cos\Phi_B+m_B)\zeta_{Bi}+M_b\cos\Phi_B\cos\Psi_B\cdot\xi_{Bi}]$$

Or, by setting up a new notation, we say:

$$(13)\quad F_{Bn}=\vec{\omega}_i^2[m_{Be}\cdot\xi_{Bi}+\Delta m_B\zeta_{Bi}]$$
$$(14)\quad F_{BP}=\vec{\omega}_i^2[m_{Be}\cdot\zeta_{Bi}+\Delta m_B\xi_{Bi}].$$

where:

$$(15)\quad \begin{cases} m_{Be}=M_b\cos^2\Psi_B+m_B;\ m_{BE}=M_b\cos^2\Phi_B+m_B \\ \Delta m_B=M_b\cos\Phi_B\cos\Psi_B. \end{cases}$$

In order to prepare for standardization it is convenient to use this notation for the forces at all mass points in the local n and P directions:

$$(16)\quad F_{jn}=\vec{\omega}_i^2[m_{je}\ \xi_{ji}+\Delta m_j\zeta_{ji}].$$
$$(17)\quad F_{jP}=\vec{\omega}_i^2[m_{je}\ \zeta_{ji}+\Delta m_j\xi_{ji}].$$

*In this case only $\bar{\bar{\gamma}}'_{DD}$ need be computed.

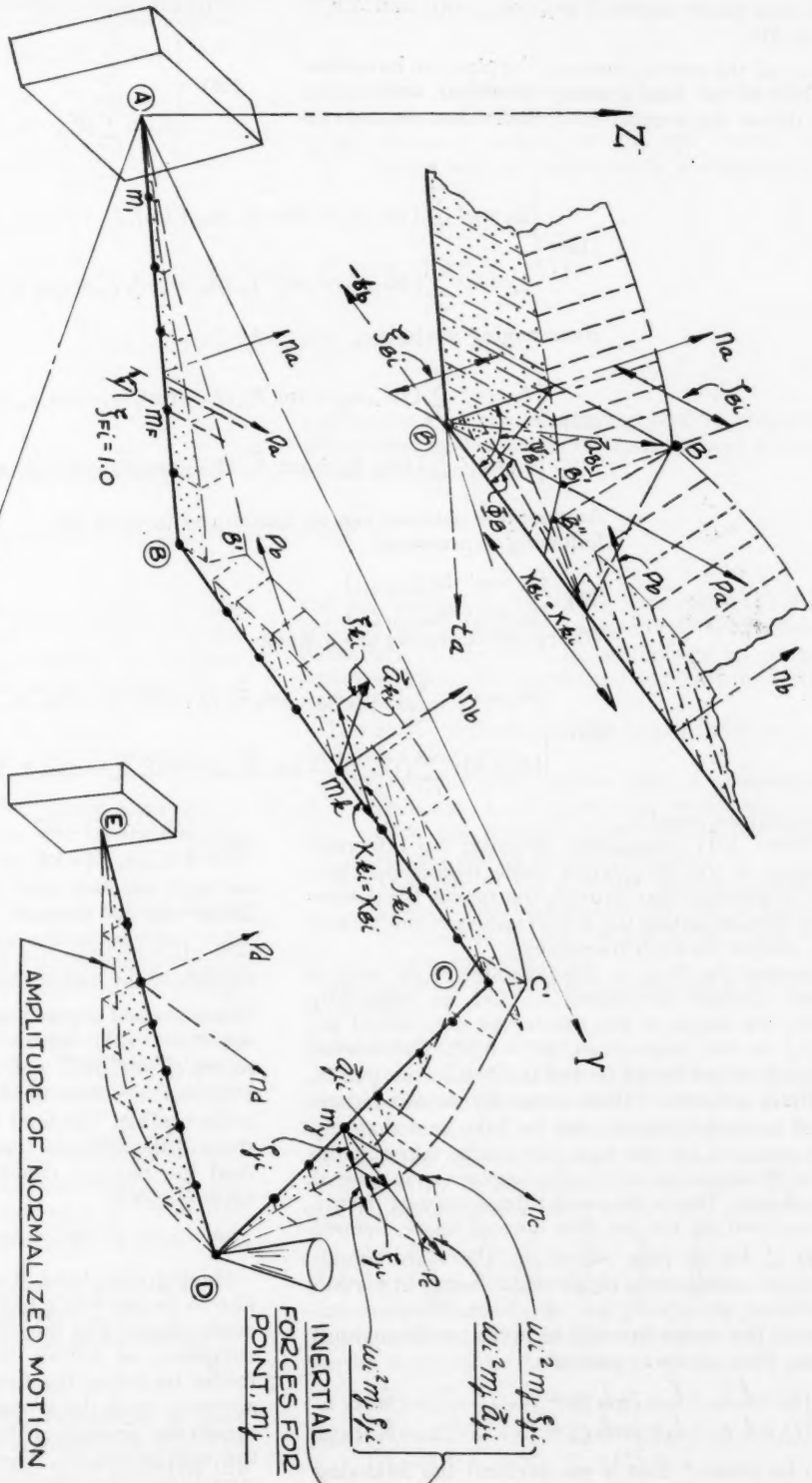


FIG. 5
NORMAL MODE CONFIGURATION
(FOR NATURAL, FREE VIBRATION AT $\omega_i$ r.p.s.)
(NORMALIZED FOR $\xi_{Fi}=1.0$)

where in this particular problem it is understood that at all mass points except B: $m_{je}=m_{je}'=m_j$ and $\Delta m_j=0$; $(j\neq B)$.

Now all the inertial forces of the pipe run have been resolved to the local n and p directions, and we can now define the normal mode deflection components at any point, $m_k$ using the previously computed static influence coefficients:

$$(18)\quad \begin{cases}\xi_{ki}=\sum_{j=1}^{j=n}[F_{jn}\cdot\alpha_{kj}+F_{jP}\cdot\bar{\alpha}_{kj}]\\ \zeta_{ki}=\sum_{j=1}^{j=n}[F_{jn}\cdot\beta_{kj}+F_{jP}\cdot\bar{\beta}_{kj}].\end{cases}$$

or

$$(19)\quad \begin{cases}\xi_{ki}=\omega_i^2\sum_{j=1}^{j=n}[(m_{je}\,\xi_{ji}+\Delta m_j\cdot\zeta_{ji})\alpha_{kj}+(m_{je}'\,\zeta_{ji}+\Delta m_j\,\xi_{ji})\bar{\alpha}_{kj}].\\ \zeta_{ki}=\omega_i^2\sum_{j=1}^{j=n}[(m_{je}\,\xi_{ji}+\Delta m_j\cdot\zeta_{ji})\beta_{kj}+(m_{je}'\,\zeta_{ji}+\Delta m_j\,\xi_{ji})\bar{\beta}_{kj}].\end{cases}$$

Rearranging we have:

$$(20)\quad \begin{cases}\xi_{ki}=\omega_i^2\sum_{j=1}^{j=n}[(m_{je}\,\alpha_{kj}+\Delta m_j\,\bar{\alpha}_{kj})\xi_{ji}+(m_{je}'\bar{\alpha}_{kj}+\Delta m_j\alpha_{kj})\zeta_{ji}]\\ \zeta_{ki}=\omega_i^2\sum_{j=1}^{j=n}[(m_{je}\,\beta_{kj}+\Delta m_j\,\bar{\beta}_{kj})\xi_{ji}+(m_{je}'\bar{\beta}_{kj}+\Delta m_j\beta_{kj})\zeta_{ji}].\end{cases}$$

An operator notation can be introduced to yield the following expressions:

$$(21)\quad \begin{cases}\xi_{ki}=\omega_i^2\cdot M_k[\xi_{ji},\zeta_{ji}]\\ \zeta_{ki}=\omega_i^2\cdot N_k[\xi_{ji},\zeta_{ji}].\end{cases}$$

Where the operators are defined:

$$(22)\quad \begin{cases}M_k[a,b]=\sum_{j=1}^{j=n}[(m_{je}\,\alpha_{kj}+\Delta m_j\,\bar{\alpha}_{kj})a+(m_{je}'\,\bar{\alpha}_{kj}+\Delta m_j\,\alpha_{kj})b]\\ N_k[a,b]=\sum_{j=1}^{j=n}[(m_{je}\,\beta_{kj}+\Delta m_j\,\bar{\beta}_{kj})a+(m_{je}'\,\bar{\beta}_{kj}+\Delta m_j\,\beta_{kj})b],\end{cases}$$

for any values, a and b.

Equations (21) completely describe the interrelationships of the ith normal mode deflections; but, more important, they provide the means for successively approximating the actual values of the normal mode shapes for each frequency.

Consider the first or fundamental mode with a natural circular frequency, $\omega_1$. Let us arbitrarily assume the shape of this mode (as normalized according to our convention, $\xi_{F1}=1.0$). This means assuming values for all $\xi_{k1}$ and $\zeta_{k1}$ for all mass points, $m_k$. These assumed values assuredly describe some sort of a curve in space, and we have said that any curve assumed by this pipe run can be taken as the sum of 2n shapes geometrically similar to the normal mode shapes. This is the same thing as saying that in any assumed set for the first normal mode, defined $\xi_{k1}'$ and $\zeta_{k1}'$ for all pass points, $m_k$, there are actually vestigal components of all mode shapes in certain proportions, $a'_1, a'_2, a'_3, \ldots a'_{2n}$ each. They are unknown at the outset but will be invariant throughout the run. This can be expressed:

$$(23)\quad \begin{cases}\xi_{k1}'=a_1'\,\xi_{k1}+a_2'\,\xi_{k2}+a_3'\,\xi_{k3}+\ldots\ldots\ldots\ldots+a_{2n}'\,\xi_{k,\,2n}\\ \zeta_{k1}'=a_1'\,\zeta_{k1}+a_2'\,\zeta_{k2}+a_3'\,\zeta_{k3}+\ldots\ldots\ldots\ldots+a_{2n}'\,\zeta_{k,\,2n}.\end{cases}$$

It can be shown* that if we perform the following operation on the first assumed shape:

$$(24)\quad \begin{cases}M_k[\xi_{j1}',\zeta_{j1}']=N_{k1}''\\ N_k[\xi_{j1}',\zeta_{j1}']=P_{k1}''\end{cases}$$

we will uncover new approximations, $\xi_{k1}''$ and $\zeta_{k1}''$, which can be defined:

(25) $\xi_{k1}''=P_{k1}''/N_{F1}''$, $\zeta_{k1}''=N_{k1}''/N_{F1}''$; which have reduced vestiges of the higher modes.

These revised approximations can be replaced in the operation (24) which will disclose still further values $\xi_{k1}'''=N_{k1}'''/N_{F1}''$ and $\zeta_{k1}''=P_{k1}'''/N_{F1}'''$. These operations can successively be repeated until little change is discernible. The final values will define a curve in space little different than the true first mode shape. And the natural (fundamental) frequency will be approximately:

(26) $\omega_1=\sqrt{1/N^r{}_{F1}}$ after the last, (r-1) st, iteration.

Having completed this determination, we should like to proceed in a like manner to compute higher mode shapes and frequencies. But an arbitrary assumption, as before, will contain vestiges of all modes including the first, and, of course, would reconverge upon the lowest as shown in the Appendix, unless the vestiges of the first mode are removed in the approximation. Then and then only will such operations converge upon the second mode shape. There is a general formula that can be used for the elimination of all modes lower than order-r in order

*See Appendix IV.

to provide a solution for the rth normal mode when those lower modes have been determined successively.

$$(27)\quad \begin{cases} \xi''_{kr}=(\xi'_{kr}-\sum_{i=1}^{i=r-1} a'_i\,\xi_{ki}) \Big/ (1.0-\sum_{i=1}^{i=r-1} a'_i) \\ \zeta''_{kr}=(\zeta'_{kr}-\sum_{i=1}^{i=r-1} a'_i\,\zeta_{ki}) \Big/ (1.0-\sum_{i=1}^{i=r-1} a'_i), \end{cases}$$

where:

$\xi_{kr}, \zeta_{kr}$ First (arbitrary) assumptions for the rth normal mode shape

$\xi_{kr}, \zeta_{kr}$ Assumed values for the rth normal mode shape with all lower mode vestiges removed

$$(28)\quad a'_i=\frac{\sum_{j=1}^{j=n}[m_{je}\,\xi_{ji}\cdot\xi'_{rj}+m_{je}\zeta_{ji}\cdot\zeta'_{jr}+\Delta m_j\,(\zeta_{ji}\,\xi'_{jr}+\xi_{ji}\,\zeta'_{jr})]}{\sum_{j=1}^{j=n}[m_{je}\,\xi^{a}_{ji}+m'_{je}\,\zeta^{a}_{ji}+2\Delta m_j\cdot\xi_{ji}\cdot\zeta_{ji}]}.$$

All terms except $a'_i$ are known.

The above formulas are derived in Appendix IV and utilize the important orthogonality property of the normal modes, which for this case and in our notation is expressible: *

$$(29)\quad \sum_{j=1}^{j=n}[m_{je}\,\xi_{ji}\cdot\xi_{jP}+m_{je}\zeta_{ji}\,\zeta_{jP}+\Delta m_j\,(\xi_{ji}\,\zeta_{jP}+\zeta_{ji}\,\xi_{jP})]=0 \text{ for } i\neq P.$$

(i and p, as indicated, infer any two different mode orders.) Repeated iterations of $\xi''_{kr}$ and $\zeta''_{kr}$ using the operations (24) will converge towards the shape of the rth normal mode. And the natural frequency of this mode will be:

(30) $\omega_r \cong \sqrt{1/N^{s}_{Fr}}$† after the (s-1) st iteration where: $N^{s}_{Fr}=M_F\,[\xi^{s-1}{}_{jr}, \zeta^{s-1}{}_{jr}]$.

The advantages of this method, which is merely an extension of a familiar treatment of structures subject to uniaxial vibrations, are numerous. For one thing, it is rather well suited to automatic computation. Also the precision of calculation is well under control. Evaluation of high order determinants, as in the method of plotting to satisfy the frequency equation, is omitted here. And all consideration of high modes of vibration, which are often of little importance, can be omitted. These determinations are vital to any considerations of forced and/or tuned vibrations of piping, as well as to the solution of shock problems.

## IV RESPONSE OF PIPE RUN TO NON-UNIFORM SHOCK

In Figure 6 the pipe run is illustrated again in this case at an arbitrary time, t, during a shock motion produced by its supports. The support shock motion is defined as follows:

(a) Anchors A and E have identical, parallel motion in the 'Z' direction defined: $\overline{Z}_A(t)$

(b) The hanger D has a motion in space defined: $\overline{X}_D(t)$, $\overline{Y}_D(t)$ $\overline{Z}_D(t)$.

The configuration A'B'C'D'E', represents a pure translation in the 'Z' direction of magnitude, $|Z_A|$. The displacement components, $n_D$, $p_D$, $t_D$, of D, define the hanger's relative excursion from its translated position at this time. Elastic deflections are referred to the translated position using the local reference axes and are defined, $n_k$, $p_k$ and $t_k$ with respect to the local n, p and t directions respectively. The absolute deflections of any point, $m_k$ are defined $\gamma_k$, $\chi_k$ and $\delta_k$ with respect to these local axes as measured from its initial position.

The elastic deflection of the run at the time, t, can be divided as follows:

(a) That due solely to the relative excursions of D, $n_D$, $p_D$, $t_D$. It is a 'static equilibrium position,' represented by the elastic components $n_{kS}$, $p_{kS}$ and $t_{kS}$ for any point $m_k$.

(b) That due to the absolute accelerations of all mass points represented by the components $n_{ke}$, $p_{ke}$ and $t_{ke}$ for the point, $m_k$. This is the 'dynamic component.'

The resultant position is represented A'B''C''D''E' in the figure.

*Static Equilibrium Position*

The relative deflections corresponding to the static equilibrium can be established in terms of the relative excursion of D if we use the influence coefficients of the reduced run for unit force components at D, first by determination of reactions, $\overline{R}_{nD}$, $\overline{R}_{pD}$, and $\overline{R}_{tD}$ corresponding only to the static equilibrium:

$$(31)\quad \begin{cases} n_D=\overline{R}_{nD}\;\alpha'_{DD}+\overline{R}_{pD}\cdot\overline{\alpha}'_{DD}-\overline{R}_{tD}\cdot\overline{\overline{\alpha}}'_{DD} \\ p_D=\overline{R}_{nD}\;\beta'_{DD}+\overline{R}_{pD}\cdot\overline{\beta}'_{DD}-\overline{R}_{tD}\cdot\overline{\overline{\beta}}'_{DD} \\ t_D=\overline{R}_{nD}\;\gamma'_{DD}+\overline{R}_{pD}\cdot\overline{\gamma}'_{DD}-\overline{R}_{tD}\cdot\overline{\overline{\gamma}}'_{DD}. \end{cases}$$

The equations, (31), are simultaneous and solvable for the reactions in the form:

$$(32)\quad \begin{cases} \overline{R}_{nD}=A'_1\cdot n_D+A'_2\cdot P_D+A'_3\cdot t_D \\ \overline{R}_{pD}=B'_1\cdot n_D+B'_2\cdot\cdot P_D+B'_3\cdot t_D \\ \overline{R}_{tD}=C'_1\cdot n_D+C'_2\cdot\cdot P_D+C'_3\cdot t_D \end{cases}$$

*The particular derivation of the orthogonality relationship for this type of structure also appears in the Appendix V.

†Superscripts refer to the number of interations.

Now for an arbitrary point, $m_k$, the static-elastic deflection in the local n and p directions can be defined, again using influence coefficients of the reduced run:

$$(33)\quad \begin{cases} n_{kS}=\bar{R}_{nD}\cdot\alpha'_{kD}+\bar{R}_{PD}\cdot\alpha_{kD}-\bar{R}_{tD}\cdot\bar{\alpha}'_{kD} \\ p_{kS}=\bar{R}_{nD}\cdot\beta'_{kD}+\bar{R}_{PD}\cdot\bar{\beta}'_{kD}-\bar{R}_{tD}\cdot\beta'_{kD}, \end{cases}$$

and, owing to the linear relationships (32), these deflections will also be linear combinations of $n_D$, $p_D$ and $t_D$ thus:

$$(34)\quad \begin{cases} n_{kS}=A_{1k}\,n_D+A_{2k}\cdot P_D+A_{3k}\cdot t_D \\ p_{kS}=B_{1k}\,n_D+B_{2k}\cdot P_D+B_{3k}\cdot t_D \end{cases}$$

where: $A'_{1k}=A_1\,\alpha'_{kD}+B_1\,\bar{\alpha}'_{kD}-C_1\,\bar{\bar{\alpha}}'_{kD}$; etc.
The axial deflection can be associated with the corner movement at B. These elastic deflections correspond to the absolute displacements:

$$(35)\quad \begin{cases} \gamma_{kS}=\bar{Z}_A\cos\phi+n_{kS}=\bar{Z}_A\cos\phi+A_{1k}\,n_D+A_{2k}\cdot p_D+A_{3k}\cdot t_D \\ \chi_{kS}=\bar{Z}_A\cos\theta+p_{kS}=\bar{Z}_A\cos\theta+B_{1k}\,n_D+B_{2k}\cdot p_D+B_{3k}\cdot t_D \end{cases}$$

Since the support displacements and shock spectra will be given with respect to the X, Y and Z axes, it is well to convert the expressions (35), noting that the relative excursions of D are*:

$$(36)\quad \begin{cases} n_D=(\bar{Z}_D-\bar{Z}_A)\cos\phi_{DZ}+\bar{X}_D\cdot\cos\phi_{DX}+\bar{Y}_D\cos\phi_{DY} \\ p_D=(\bar{Z}_D-\bar{Z}_A)\cos\theta_{DZ}+\bar{X}_D\cdot\cos\theta_{DX}+\bar{Y}_D\cos\theta_{DY} \\ t_D=(\bar{Z}_D-\bar{Z}_A)\cos\pi_{DZ}+\bar{X}_D\cdot\cos\pi_{DX}+\bar{Y}_D\cos\pi_{DY}. \end{cases}$$

The results of substituting these equations (36) in (35) will be:

$$(37)\quad \begin{cases} \gamma_{kS}=C_{1k}\cdot\bar{X}_D+C_{2k}\cdot\bar{Y}_D+C_{3k}\cdot\bar{Z}_D+C_{4k}\cdot\bar{Z}_A \\ \chi_{kS}=D_{1k}\cdot\bar{X}_D+D_{2k}\cdot\bar{Y}_D+D_{3k}\cdot\bar{Z}_D+D_{4k}\cdot\bar{Z}_A, \end{cases}$$

where:

$$(38)\quad \begin{cases} C_{1k}=A_{1k}\cos\phi_{DX}+A_{2k}\cos\theta_{DX}+A_{3k}\cos\pi_{DX} \\ C_{2k}=A_{1k}\cos\phi_{DY}+A_{2k}\cos\theta_{DY}+A_{3k}\cos\pi_{DY} \\ C_{3k}=A_{1k}\cos\phi_{DZ}+A_{2k}\cos\theta_{DZ}+A_{3k}\cos\pi_{DZ} \\ C_{4k}=\cos\phi-C_{3k} \\ D_{1k}=B_{1k}\cos\phi_{DX}+B_{2k}\cos\theta_{DX}+B_{3k}\cos\pi_{DX} \\ D_{2k}=B_{1k}\cos\phi_{DY}+B_{2k}\cos\theta_{DY}+B_{3k}\cos\pi_{DY} \\ D_{3k}=B_{1k}\cos\phi_{DZ}+B_{2k}\cos\theta_{DZ}+B_{3k}\cos\pi_{DZ} \\ D_{4k}=\cos\theta-D_{3k}. \end{cases}$$

*Dynamic Components*

As we have noted, these dynamic component deflections are due solely to the absolute inertial forces of all the mass points. The forces at the point $m_k$ in leg b will be $-m_k\ddot{\gamma}_k$, $-m_k\ddot{\chi}_k$, and $-m_k\ddot{\delta}_k$ in the $n_b$, $p_b$ and $t_b$ directions respectively.

Consider the tangential force $-m_k\ddot{\delta}_k$ which can exist for points $m_k$ in leg b (since we are assuming that actual axial forces in legs c and d will not cause appreciable flexural or torsional action). Then for the whole of leg b the total tangential force will be $-M_b\ddot{\delta}_b$. But, the absolute tangential acceleration of leg b actually is related to the acceleration components $\ddot{\gamma}_B$ and $\ddot{\chi}_B$ of the point B in the $n_a$ and $p_a$ directions. We have:

$$(39)\quad \ddot{\delta}_B=\ddot{\gamma}_B\cos\Psi_B+\ddot{\chi}_B\cos\Phi_B.$$

Then the inertial force $-M_b\cdot\ddot{\delta}_b$ will have components:

$$(40)\quad \begin{cases} -M_b(\ddot{\gamma}_B\cos\Psi_B+\ddot{\chi}_B\cos\Phi_B)\cos\Psi_B \\ -M_b(\ddot{\gamma}_B\cos\Psi_B+\ddot{\chi}_B\cos\Phi_B)\cos\Phi_B \end{cases}$$

Then if we add the effect of the lumped mass at B we have for the total inertial force at B:

$$(41)\quad \begin{cases} -[(M_b\cos^2\Psi_B+m_B)\,\gamma_B+(M_b\cos\Phi_B\cos\Psi_B)\,\chi_B] & \text{in the } n_a \text{ direction} \\ -[(M_b\cos^2\Phi_B\cdot\cos\Psi_B)\,\gamma_B+(M_b\cos^2\Phi_B+m_B)\,\chi_B] & \text{in the } p_a \text{ direction.} \end{cases}$$

Or, using our abbreviated notation (15) of the previous section, the forces in the $n_a$ and $p_a$ directions respectively are:

$$(42)\quad \begin{cases} -(m_{Be}\ddot{\chi}_B+\Delta m_B\cdot\ddot{\chi}_B) \\ -(m'_{Be}\ddot{\kappa}_B+\Delta m_B\cdot\ddot{\gamma}_B) \end{cases}$$

And again to maintain generality we use this notation for all mass points; we say that the absolute inertial forces for any point $m_j$ are:

$$(43)\quad \begin{cases} F_{jn}=-(m_{je}\ddot{\gamma}_j+\Delta m_j\ddot{\chi}_j) & \text{in the local n direction} \\ F_{jp}=-(m'_{je}\ddot{\chi}_j+\Delta m_j\ddot{\gamma}_j) & \text{in the local p direction} \end{cases}$$

where it is understood in this case that for all points except B:

$$m_{je}=m'_{je}=m_j \text{ and } \Delta m_j=0.$$

Now the dynamic components of deflection for a point, $m_k$ will be:

$$(44)\quad \begin{cases} n_{ke}=\sum_{j=1}^{j=n}(F_{jn}\cdot\alpha_{kj}+F_{jp}\cdot\alpha_{kj}) \\ p_{ke}=\sum_{j=1}^{j=n}(F_{jn}\cdot\beta_{kj}+F_{jp}\cdot\beta_{kj}), \end{cases}$$

or using (43):

$$(45)\quad \begin{cases} n_{ke}=-\sum_{j=1}^{j=n}[(m_{je}\alpha_{kj}+\Delta m_j\bar{\alpha}_{kj})\ddot{\gamma}_j+(m_{je}\bar{\alpha}_{kj}+\Delta m_j\,\alpha_{kj})\ddot{\chi}_j] \\ p_{ke}=-\sum_{j=1}^{j=n}[(m_{je}\beta_{kj}+\Delta m_j\bar{\beta}_{kj})\ddot{\gamma}_j+(m_{je}\bar{\beta}_{kj}+\Delta m_j\beta_{kj})\ddot{\chi}_j] \end{cases}$$

*See Figure 6 for angles at D.

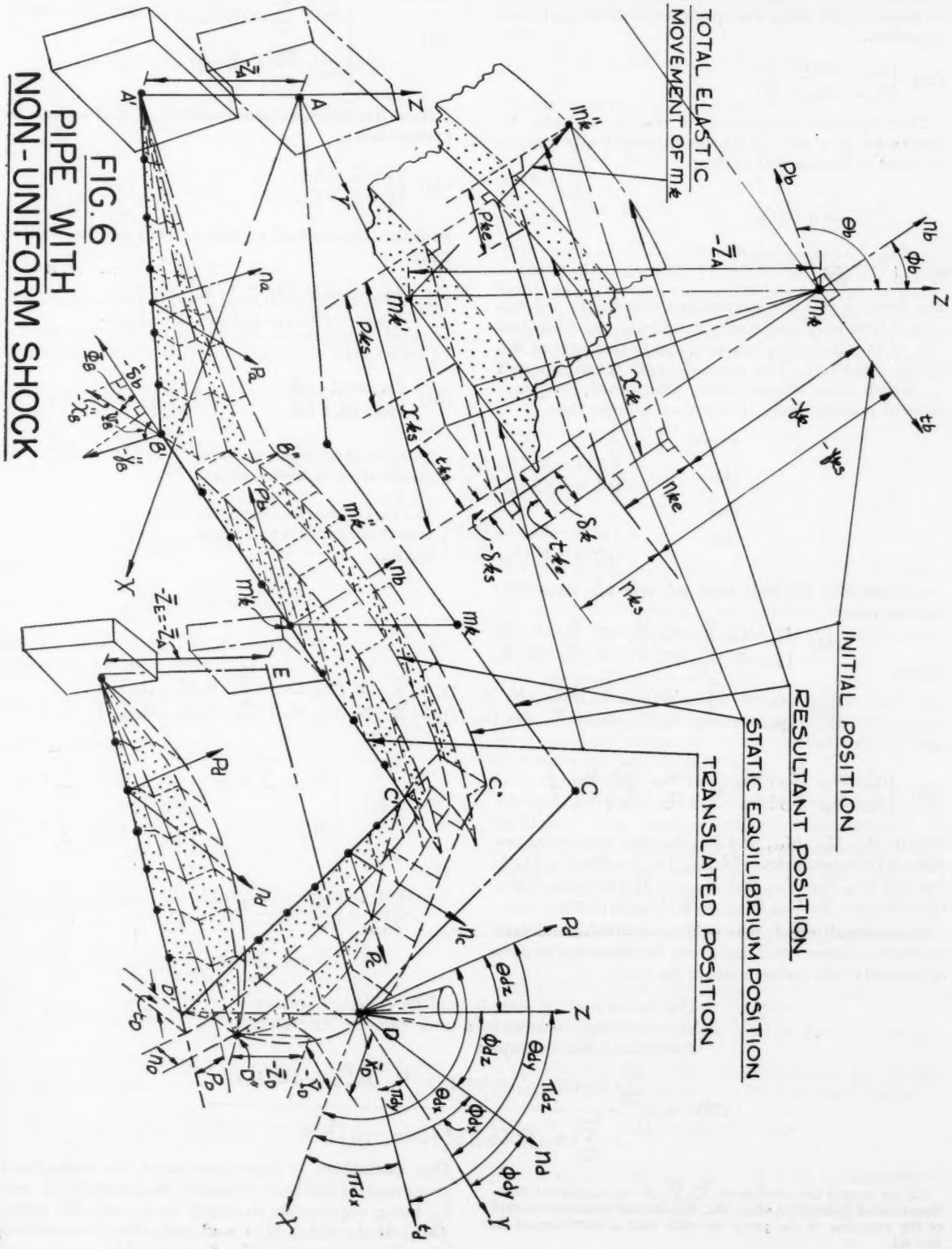


FIG. 6 PIPE WITH NON-UNIFORM SHOCK

We have noted in the previous section that this can be abbreviated using the operator notation (22), and therefore:

$$(46)\quad \begin{cases} n_{ke} = -M_k[\ddot{\gamma}_j, \ddot{\chi}_j] \\ P_{ke} = -N_k[\ddot{\gamma}_j, \ddot{\chi}_j] \end{cases}$$

This dynamic component, of course, can also be expressed as a sum of curves geometrically similar to those of the normal modes:

$$(47)\quad \begin{cases} n_{ke} = \sum_{i=1}^{i=2n} q_i(t) \cdot \xi_{ki} \\ P_{ke} = \sum_{i=1}^{i=2n} q_i(t) \cdot \zeta_{ki} \end{cases}$$

The term, $q_i(t)$, is a generalized coordinate, a function of time only, and it can be taken as the contribution of the ith normal mode shape to this part of the elastic deflection. The normal mode terms, $\xi_{ki}$ and $\zeta_{ki}$, which have already been determined, are functions of position only. It therefore follows that:

$$(48)\quad \begin{cases} n_{ke} = \sum_{i=1}^{i=2n} q_i(t) \cdot \xi_{ki} \\ p_{ke} = \sum_{i=1}^{i=2n} \ddot{q}_i(t) \cdot \zeta_{ki} \end{cases}$$

Now the absolute accelerations, $\gamma_j$ and $\chi_j$, can be broken down:

$$(49)\quad \begin{cases} \ddot{\gamma}_j = \ddot{\gamma}_{js} + \ddot{n}_{je} \\ \ddot{\chi}_j = \ddot{\chi}_{js} + \ddot{p}_{je}. \end{cases}$$

And this means that equations (46) can be written thus:

$$(50)\quad \begin{cases} n_{ke} = -\{M_k[\ddot{\gamma}_{js}, \ddot{\chi}_{js}] + M_k\ [\ddot{n}_{je}, \ddot{p}_{je}]\} \\ p_{ke} = -\{N_k[\ddot{\gamma}_{js}, \ddot{\chi}_{js}] + N_k\ [\ddot{n}_{je}, \ddot{p}_{je}]\}, \end{cases}$$

or let us say:

$$(51)\quad \begin{cases} n_{ke} = n'_{ke} + n''_{ke} \\ p_{ke} = p'_{ko} + p''_{ke}, \end{cases}$$

where

$$(52)\quad \left.\begin{cases} n'_{ke} = -M_k[\ddot{\gamma}_{ks}, \ddot{\chi}_{ks}] \\ p'_{ke} = -N_k[\ddot{\gamma}_{ks}, \ddot{\chi}_{ks}] \end{cases}\right\} \text{The part of the dynamic component attributable to motions } \ddot{\gamma}_{js}, \ddot{\chi}_{js}.$$

and

$$(53)\quad \left.\begin{cases} n''_{ke} = -M_k[\ddot{n}_{je}, \ddot{p}_{je}] \\ p''_{ke} = -N_k[\ddot{n}_{je}, \ddot{p}_{je}] \end{cases}\right\} \text{The part of the dynamic component attributable to motions } \ddot{n}_{je}, \ddot{p}_{je}.$$

Considering the first part, $n'_{ke}$ and $p'_{ke}$, from (37) we can note:

$$(54)\quad \begin{cases} \ddot{\gamma}_{js} = C_{1j}\ddot{X}_D + C_{2j}\ddot{Y}_D + C_{3j}\ddot{Z}_D + C_{4j}\ddot{Z}_A \\ \ddot{\chi}_{js} = D_{1j}\ddot{X}_D + D_{2j}\ddot{Y}_D + D_{3j}\ddot{Z}_D + D_{4j}\ddot{Z}_A. \end{cases}$$

Then:

$$(55)\quad \begin{cases} n'_{ke} = -\{\ddot{X}_D \cdot M_k[C_{1j}, D_{1j}] + \ddot{Y}_D \cdot M_k\ [C_{2j}, D_{2j}] + \ddot{Z}_D \cdot M_k\ [C_{3j}, D_{3j}] + \ddot{Z}_A \cdot M_k[C_{4j}, D_{4j}]\} \\ p_{ke} = -\{\ddot{X}_D \cdot N_k[C_{1j}, D_{1j}] + \ddot{Y}_D \cdot N_k\ [C_{2j}, D_{2j}] + \ddot{Z}_D \cdot N_k\ [C_{3j}, D_{3j}] + \ddot{Z}_A \cdot N_k[C_{4j}, D_{4j}]\}, \end{cases}$$

or

$$(56)\quad \begin{cases} n'_{ke} = M_{1k} \cdot \ddot{X}_D + M_{2k} \cdot \ddot{Y}_D + M_{3k} \cdot \ddot{Z}_D + M_{4k} \cdot \ddot{Z}_A \\ p'_{ke} = N_{1k} \cdot \ddot{X}_D + N_{2k} \cdot \ddot{Y}_D + N_{3k} \cdot \ddot{Z}_D + N_{4k} \cdot \ddot{Z}_A. \end{cases}$$

Where $M_{1k}$, $M_{2k}$, $M_{3k}$, and $M_{4k}$ are the numerical results of the operations,—$M_k[C_{1j}, D_{1j}]$, —$M_k[C_{2j}, D_{2j}]$, etc. and $N_{1k}$, $N_{2k}$, $N_{3k}$, and $N_{4k}$ are the results of the operations— $N_k[C_{1j}, D_{1j}]$, —$N_k[C_{2j}, D_{2j}]$, etc.

Now actually each pair of these coefficients define curves* in space which again can be taken as the sum of normal mode components in the form:

$$(57)\quad \begin{cases} \text{(a)} \begin{cases} M_{1k} = \sum_{i=1}^{i=2n} e_i\ \xi_{ki} \\ N_{1k} = \sum_{i=1}^{i=2n} e_i\ \zeta_{ki} \end{cases} \quad \text{(b)} \begin{cases} M_{2k} = \sum_{i=1}^{i=2n} f_i\ \xi_{ki} \\ N_{2k} = \sum_{i=1}^{i=2n} f_i\ \zeta_{ki} \end{cases} \\ \text{(c)} \begin{cases} M_{3k} = \sum_{i=1}^{i=2n} g_i\ \xi_{ki} \\ N_{3k} = \sum_{i=1}^{i=2n} g_i\ \zeta_{ki} \end{cases} \quad \text{(d)} \begin{cases} M_{4k} = \sum_{i=1}^{i=2n} h_i\ \xi_{ki} \\ N_{4k} = \sum_{i=1}^{i=2n} h_i\ \zeta_{ki} \end{cases} \end{cases}$$

The terms $e_i$, $f_i$, $g$ and $h_i$ will be called *characteristic response parameters* and can be discretely evaluated.† For example:

$$(58)\quad e_i = \frac{\sum_{j=1}^{j=n} \{M_{1j}(m_{je} \cdot \xi_{j1} + \Delta m_j \zeta_{j1}) + N_{1j}(m'_{je} \zeta_{j1} + \Delta m_j \xi_{j1})\}}{\sum_{j=1}^{j=n} \{m_{je} \xi_{j1}^2 + m'_{je} \zeta_{j1}^2 + 2\Delta m_j \cdot \xi_{j1} \cdot \zeta_{j1}\}}.$$

This evaluation is dependent upon the orthogonal properties of the normal modes structure, $f_i$, $g_i$ and $h_i$, being expressible similarly to $c_i$ with the pairs, $(M_{2j}, N_{2j})$, $(M_{3j}, N_{3j})$ and $(M_{4j}, N_{4j})$, respectively replacing the pair $(M_{1j}, N_{1j})$ in (58).

*If we regard the coefficients $\ddot{X}_D$, $\ddot{Y}_D$ etc. as numerical, non-dimensional quantities, then $M_{1k}$, $N_{1k}$ etc. correspond to a part of the response of the point, $m_k$ with unit acceleration of D, (or A).

†See Appendix VI for derivation.

The dynamically induced deflections attributable to the accelerations $\ddot{\gamma}_{js}$, $\ddot{\chi}_{js}$ are:

$$(59)\quad \begin{cases} n_{ke}=\sum_{i=1}^{i=2n}(e_i\ddot{\bar{X}}_D+f_i\cdot\ddot{\bar{Y}}_D+g_i\ddot{\bar{Z}}_D+h_i\ddot{\bar{Z}}_A)\xi_{ki} \\ p_{ke}=\sum_{i=1}^{i=2n}(e_i\ddot{\bar{X}}_D+f_i\cdot\ddot{\bar{Y}}_D+g_i\ddot{\bar{Z}}_D+h_i\ddot{\bar{Z}}_A)\zeta_{ki}, \end{cases}$$

or

$$(60)\quad \begin{cases} n'_{ke}=\sum_{i=1}^{i=2n}Q_i(t)\cdot\xi_{ki} \\ p'_{ke}=\sum_{i=1}^{i=2n}Q_i(t)\cdot\zeta_{ki}, \end{cases}$$

(61) where $Q_i(t)=e_i\ddot{\bar{X}}_D+f_i\cdot\ddot{\bar{Y}}_D+g_i\ddot{\bar{Z}}_D+h_i\ddot{\bar{Z}}_A$

Now the other part of the dynamically induced deflection is from (53) and (48):

$$\begin{cases} n''_{ke}=-M_k[(\sum_{i=1}^{i=2n}\ddot{q}_i(t)\xi_{ji}),(\sum_{i=1}^{i=2n}\ddot{q}_i(t)\zeta_{ji})] \\ p''_{ke}=-N_k[(\sum_{i=1}^{i=2n}\ddot{q}_i(t)\xi_{ji}),(\sum_{i=1}^{i=2n}\ddot{q}_i(t)\zeta_{ji})] \end{cases}$$

or

$$(62)\quad \begin{cases} n''_{ke}=-\sum_{i=1}^{i=2n}\{\ddot{q}_i(t)\cdot M_k[\xi_{ji},\zeta_{ji}]\} \\ p''_{ke}=-\sum_{i=1}^{i=2n}\ddot{q}_i(t)\cdot N_k\ [\xi_{ji},\zeta_{ji}]\}. \end{cases}$$

But now if we recall our discussion of normal mode evaluation we have from (21)

$$(63)\quad \begin{cases} M_k[\xi_{ji},\zeta_{ji}]=\xi_{ki}/\omega_i^2 \\ N_k[\xi_{ji},\zeta_{ji}]=\zeta_{ki}/\omega_i^2 \end{cases}$$

and therefore:

$$(64)\quad \begin{cases} n''_{ke}=-\sum_{i=1}^{i=2n}q_i(t)\cdot\zeta_{ki}/\omega_i^2 \\ p''_{ke}=-\sum_{i=1}^{i=2n}q_i(t)\cdot\xi_{ki}/\omega_i^2 \end{cases}$$

We are now ready to express the complete dynamic component of deflection using (60) and (64):

$$(65)\quad \begin{cases} n_{ke}=n'_{ke}+n''_{ke}=\sum_{i=1}^{i=2n}[Q_i(t)-\ddot{q}_i(t)/\omega_i^2]\cdot\xi_{ki} \\ p_{ke}=p'_{ke}+p''_{ke}=\sum_{i=1}^{i=2n}[Q_i(t)-\ddot{q}_i(t)/\omega_i^2]\cdot\zeta_{ki}. \end{cases}$$

Or using the generalized coordinates for the terms $n_{ke}$ and $p_{ke}$ we have:

$$\begin{cases} \sum_{i=1}^{i=2n}q_i(t)\cdot\xi_{ki}=\sum_{i=1}^{i=2n}[Q_i(t)-\ddot{q}_i(t)/\omega_i^2]\xi_{ki} \\ \sum_{i=1}^{i=2n}q_i(t)\cdot\zeta_{ki}=\sum_{i=1}^{i=2n}[Q_i(t)-\ddot{q}_i(t)/\omega_i^2]\zeta_{ki} \end{cases}$$

The entire equations can be put under single summation signs:

$$(66)\quad \begin{aligned} &\sum_{i=1}^{i=2n}[\ddot{q}_i(t)+\omega_i^2\cdot q_i(t)-\omega_i^2Q_i(t)]\xi_{ki}/\omega_i^2=0 \\ &\sum_{i=1}^{i=2n}[\ddot{q}_i(t)+\omega_i^2\cdot q_i(t)-\omega_i^2Q_i(t)]\zeta_{ki}/\omega_i^2=0. \end{aligned}$$

Which in turn could be written:

$$(67)\quad \begin{cases} \sum_{i=1}^{i=2n}C_i\cdot\xi_{ki}=0 \\ \sum_{i=1}^{i=2n}C_i\cdot\zeta_{ki}=0 \end{cases}$$

(68) where: $C_i=\ddot{q}_i(t)+\omega_i^2q_i(t)-\omega_i^2Q_i(t)]\cdot/\omega_i^2$

The equations (67) could be written for every point, $m_k$, (i.e. with two equations for each of the n points), and they would constitute a set of 2n simultaneous, homogeneous equations with 2n unknowns, $C_i$. Being homogeneous, they would have non-zero solutions for $C_i$ only if the determinant, $\nabla$, were to vanish.

Where:

$$(69)\quad \nabla=\begin{vmatrix} \xi_{11},\xi_{12}\ \cdots\cdots\ \xi_{1,2n} \\ \xi_{21},\xi_{22}\ \cdots\cdots\ \xi_{2,2n} \\ \vdots\ \ \vdots\ \ \cdots\cdots\ \ \vdots \\ \xi_{n1},\xi_{n2}\ \cdots\cdots\ \xi_{n,2n} \\ \zeta_{11},\zeta_{12}\ \cdots\cdots\ \zeta_{1,2n} \\ \vdots\ \ \vdots\ \ \cdots\cdots\ \ \vdots \\ \zeta_{n1},\zeta_{n2}\ \cdots\cdots\ \zeta_{n,2n} \end{vmatrix}.$$

But this is not the case, and therefore the solutions for $C_i$ are zero. Noting our definition (68) of $C_i$, we are saying that a series of independent equations can be written regarding each modal part of the dynamic component of response:

(70) $\ddot{q}(t)+\omega_i^2\cdot\ q_i(t)=\omega_i^2Q_i(t).$

As with many transient problems we find that these resulting differential equations are very similar to that of a simple harmonic oscillator of one degree of freedom of the form:

(71) $\ddot{q}_i(t)+\omega_n^2q(t)=F(t)/m,$

where $\omega_n=\sqrt{k/m}$ is the natural frequency of the oscillator. The term, $\omega_i^2Q_i(t)$, corresponds to $F^{(t)}/m$ in (71). When such a simple oscillator is exposed to a transient motion, say, from the foundation of its spring which exerts a force, $F(t)$, its response is the sum of those for a series of step functions* with the net result that at the time, t, its displacement, $q(t)$, is expressible:

$$q(t)=\frac{\omega_n}{k}\int_0^t F(\tau)\sin\omega_n(t-\tau)\,d\tau=\frac{1}{\omega_n}\int_0^t F\frac{(\tau)}{m}:\sin\omega_n(t-\tau)\,d\tau$$

where $\tau$ is an intermediate time between the inception of the force and t.

For the pipe run, noting the above analogy, we can conclude that our equation (70) has the solution:

$$(72)\ q_i(t)=\frac{1}{\omega_i}\int_0^t\omega_iQ_i(\tau)\sin\omega_i(t-\tau)\,d\tau$$

$$=\omega_i\int_0^tQ_i(\tau)\sin\omega_i(t-\tau)\ d\tau, \text{ if } Q_i(t) \text{ is a transient.}$$

And recalling the definition (61) of $Q_i(t)$ we can write:

*This discussion is well amplified by Blake and Swick (2).

$$(73)\quad q_i(t)=e_i[\omega_i\int_o^t \ddot{X}_D(\tau)\sin\omega_i(t-\tau)\,d\tau]+f_i[\omega_i\int_o^t \ddot{Y}_D(\tau)\sin\omega_i(t-\tau)\,d\tau]$$
$$+g_i[\omega_i\int_o^t \ddot{Z}_D(\tau)\sin\omega_i(t-\tau)\,d\tau]+h_i[\omega_i\int_o^t \ddot{Z}_A(\tau)\sin\omega_i(t-\tau)d\tau]$$

This equation, in essence, brings us to the boundary of our problem. For the coefficients of $e_i$, $f_i$, $g_i$, and $h_i$ have to do with the time histories of the supports. We must, therefore, talk of the input data to the shock problem. Ideally as conditions of the problem we should like to have these coefficients presented to us at the outset as functions of time.* Then we would have values of $q_i(t)$ for all i and for all t after the inception of shock. If, in addition, we had presented as data the support displacements† as functions of time, we could completely predict the history of the piping system itself as a function of time and observe for maxima. When this is not available, our 'second best' is to have available shock spectra which for each frequency define maximum values of the coefficients in (73) and which we shall define:

$$(74)\quad \begin{cases} (N_{Xi})_D=[\omega_i\int_o^t \ddot{X}_D(\tau)\sin\omega_i(t-\tau)\,]_{max} \\ (N_{Yi})_D=[\omega_i\int_o^t \ddot{Y}_D(\tau)\sin\omega_i(t-\tau)\,]_{max} \\ (N_{Zi})_D=[\omega_i\int_o^t \ddot{Z}_D(\tau)\sin\omega_i(t-\tau)\,]_{max} \\ (N_{Zi})_A=[\omega_i\int_o^t \ddot{Z}_A(\tau)\sin\omega_i(t-\tau)\,]_{max} \end{cases}$$

The numerical values of these quantities for a broad range of frequencies and for representative structure are often plotted to provide indices of the intensity of shock. For example, a reed gage, a series of single-degree-of-freedom systems of varying frequencies, when subjected to shock motion of representative structure will provide the means for constructing such a plot. And the plot itself is termed the shock spectrum of the resultant motion of the structure to which the gage is attached and in the direction of its stimulation. If this data can be soundly predicted, then we could say of our system that a limiting response corresponding to the ith component would be:

$$(75)\quad [q_i(t)]_{max}=e_i(N_{Xi})_D+f_i(N_{Yi})_D+g_i(N_{Zi})_D+h_i(N_{Zi})_A.$$

Actually the system as a whole tends to respond to transient motion in all its natural modes. We can envelope the maximum possible response as the sum of the maxima of all the component natural frequencies thus:

$$(76)\quad \begin{cases} [n_{ke}]_{max}=\sum_{i=1}^{i=2n}\{\xi_{ki}[e_i(N_{Xi})_D+f_i(N_{Yi})_D+g_i(N_{Zi})_D+h_i(N_{Zi})_A]\} \\ [p_{ke}]_{max}=\sum_{i=1}^{i=2n}\{\zeta_{ki}[e_i(N_{Xi})_D+f_i(N_{Yi})_D+g_i(N_{Zi})_D+h_i(N_{Zi})_A]\}. \end{cases}$$

This limiting solution would actually be computed only for a few of the lower modes of vibration.

To this limiting solution for the 'dynamic component' we can add a limiting solution for the static equilibrium for the maximum relative travel to be expected of the hanger at D with respect to the other two supports as indicated by equation (33), and:

$$(77)\quad \begin{cases} [n_k]_{max}=[n_{ks}]_{max}+[n_{ke}]_{max} \\ [p_k]_{max}=[p_{ks}]_{max}+[p_{ke}]_{max} \end{cases}$$

Forces and moments and hence stresses are, of course, dependent upon the inertial loads corresponding to the estimated, (or limiting) deflection of the pipe run. Relative forces are expressible:

$$F'_{jn}=-m_j\sum_{i=1}^{i=2n}q_i(t)\cdot\xi_{ji};\ F'_{jp}=-m_j\sum_{i=1}^{i=2n}q_i(t)\cdot\zeta_{ji}$$

in the local p and n directions at $m_j$ respectively. And from (70) we note that:

$$\ddot{q}_i(t)=\omega_i^2[Q_i(t)-q_i(t)]$$
$$=\omega_i^2[e_i\ddot{X}_D+f_i\cdot\ddot{Y}_D+g_i:\ddot{Z}_D+h_i\cdot\ddot{Z}_A-q_i(t).]$$

The inertial force components will be:

*Here is when analog computers can give results if time history of supports can be predicted.

†This is in order to ascertain the static-elastic contribution.

$$(78)\quad \left\{\begin{aligned} F'_{jn} &= -m_j \sum_{i=1}^{i=2n} \omega_i^2 \xi_{ji}[e_i \ddot{X}_D(t) + f_i \cdot \ddot{Y}_D(t) + g_i Z_D(t) + h_i \ddot{Z}_A(t) - q_i(t)] \\ F'_{jP} &= -m_j \sum_{i=1}^{i=2n} \omega_i^2 \zeta_{ji}[e_i \ddot{X}_D(t) + f_i \cdot \ddot{Y}_D(t) + g_i \ddot{Z}_D(t) + h_i \ddot{Z}_A(t) - q_i(t)]. \end{aligned}\right\}$$

Relative Forces only

Here again we face the problem of data. To solve directly we would need to know the instantaneous accelerations of all the supports at the time t—in short, the time history of the supports' accelerations. If this latter data is unavailable, then we are forced to a longer approach. The dynamic component deflections have limiting values from (76), which in all practical cases can be cut off at a few modes. Then the force systems, $F_{jn}$ and $F_{jP}$, are related to $n_{ke}$ and $p_{ke}$, as computed, by the relationship:

$$(79)\quad \left\{\begin{aligned} \sum_{j=n}^{i=2n} [F_{jn} \cdot \alpha_{kj} + F_{jP} \cdot \overline{\alpha}_{kj}] &= n_{ke} \\ \sum_{j=n}^{i=2n} [F_{jn} \cdot \beta_{kj} + F_{jP} : \overline{\beta}_{kj}] &= p_{ke}. \end{aligned}\right\}$$

These equations can be written for each of the n points, and constitute a linear set simultaneous and solvable for all values, $F_{jn}$, $F_{jp}$.

With $F_{jn}$ and $F_{jp}$ known, the data from the influence coefficient work can be used. These data would consist of end moments and forces in the pipe run and (if desired) field moments and forces, corresponding in each case to unit loads in the n and p directions at each of the n points. The aggregate moment or force at any point corresponding to the pattern, $n_{ke}$, $p_{ke}$, can be obtained by factoring the individual values for the unit force application by the appropriate value of $F_{jn}$ or $F_{jp}$.

To these forces and moments must be added the effects of the static equilibrium position. Here we can use similar data corresponding to unit force applications at D for the reduced run (hanger removed). This means we must use the best estimate we can make of the maximum relative movement of D if we lack time histories of the supports' displacements. First, under these circumstances we would derive the instantaneous values of the static reaction components at D using equations (32); then with numerical evaluation of this reaction at D in hand, we can similarly evaluate the static parts of the bending and flexural moments in the pipe run (together with forces) by a factoring and superposition of the values they would have with unit forces in the three directions $n_d$, $p_d$ and $t_1$ at D.

The sums of the static and dynamic components provide enveloping values of internal and end moments and forces. We have, in short, estimates of the limiting values.

This is about the best that we can do when our data consists of support shock spectra and estimated maximum support deflections. As we have shown, the inclusion of the time history of support motion as data would permit more direct solutions. If this were so, we could carry out the integrations of equation (73) for $q_i(t)$ for a nominal number of modes. (This would involve approximate numerical or graphical integration, or possibly, analog computer.) And equation (78) shows a part solution for the forces at the mass points when $\ddot{X}_D$, $\ddot{Y}_D$, $\ddot{Z}_D$, $\ddot{Z}A$ and $q_i(t)$ are known, for any specific time. In brief, we could then construct a predicted time history of the pipe run, where obviously the effects of the instantaneous static equilibrium could be readily factored in by the methods discussed above. But in this case we would use the *known* support deflections as functions of time.

## V OBSERVATIONS

### *Discussion of Algebraic Development*

It is an unfortunate fact that the algebra connected with stress problems of piping has a rather cluttered appearance which, sadly enough, continues in this study of dynamic action. Its effect is to mask essentially simple principles. The terminal equation (70), which expresses matters in generalized coordinates, is a very familiar form, and it should be noted that it is equally valid for undamped, steady state vibration when the stimulus came from the motion of the system's supports. That the terminal equation of motion of a highly distributed mass system should take on this simplicity, should be no surprise, for it is a common matter in other complicated geometries. The motion of plates, shells, aircraft wings, turbine buckets, and the like can be described similarly. And, of course, the ability to separate the motion components into simple equations involving each modal property is implicit in the classical equations of Lagrange which hold for any elastic structures. The analogy to single degree of freedom systems can be extended into cases of viscous damping, which is important to steady state vibration. The success of the latter will depend on our subsequent ability to estimate suitable damping constants for piping systems.

All of this tends to show that we are up against nothing particularly new. The required static properties demand a multiple combination of processes already familiar in thermal stress calculations. And the iterative processes for natural frequencies and normal modes have already been routinized for computer solutions. With these two classes of properties in hand we have recourse to classical principles.

Our biggest concerns at this juncture should have to do with generality, with computation procedure, and with probability of occurance of shock stress levels. The possibilities of analysis for partially plastic action are important but can only be touched upon in this paper.

### *Generality*

The analysis of piping is strongly mixed up with the economics of so doing. Computation programming of the type we can forecast here can scarcely be justified unless it will be meaningful for quite a variety of piping systems.

The actual run chosen for example here is rather simple. The existence of an intermediate hanger and the possibilities of sway parallel to an axis, however, make it reasonably general. It seems probable that a computation program could be set up for three or more anchors which would still be applicable to cases such as the illustrations. It seems probable, too, that a program would be set up to handle first the properties of runs without hangers (i.e. reduced pipe runs). Under these circumstances the inclusion of one or more hangers would be handled by ancillary but general subroutines whose principal functions would be to solve simultaneous equations such as (4) in this text and the algebraic type represented by (5), which corrects the influence coefficients of the reduced run. Both pipe hangers and anchors may have some internal elasticity for which a general program could be prepared. Under these circumstances the equations (3) would have the form:

$$\frac{\partial V}{\partial R_{nD}} = -R_{nD}/k_D$$

which particular equation would imply a hanger spring constant in the n direction of magnitude $k_D$. This does not appear to be a major complication; it is obvious that the equivalent algebraic equation would remain linear in all the redundants.

In the illustrative problem bend flexibility would be included in computation of influence coefficients, but in this example case we have ignored the relative axial displacements between the mass points in leg b and the figurative intercept, B. This is probably reasonable for a large number of cases. But for long radius bends and compound bends it would not be fair, and, in effect this turns the problem into a 2n-plus-one degree-of-freedom case. Thus, the effects of a unit force coaxial with leg b would have to be statically treated. In short, it adds to the number of influence coefficients to be determined. And the expressions (28) for a′ (lower mode removal) and for (58) (the characteristic response parameters) would be modified by reasoning identical to that already shown here. This situation would be repeated for an exceedingly long radius bend where it would only be realistic to situate a lumped mass point within the bend itself. Such a point would require three influence coefficients with respect to all other mass points. In these cases the equivalent mass terms (15) would contract.

The shock problem that has been presented here has some qualitative realism in that the anchors are normally rather heavy items of equipment such as heat exchangers, pumps or the like which are usually built rather carefully into major structural units of the vessel. Hangers, on the other hand, can often be tied into lighter, more flexible structural elements. As such, one would expect the hanger to have quite a different shock motion than that of the anchors. The specific equations describing static equilibrium and the equations for the coefficients, such as (38) would require some generalizing and fitting to suit the needs of other problems, but again one would expect the same general forms to prevail.

*Computation Procedure*

The remarks on generality bear directly on the feasibility of automatic computation without which we can expect little utility. Fortunately, any specific influence coefficient calculation is strongly similar to a typical thermal stress problem for which there is a considerable computation history. The existence of a concentrated load in the elastic problem has not been unforeseen, as indicated by the Kellogg presentation (1). The major development here, will be the set-up of a generalized program that can rapidly shift from one unit force application to another. It would be preferable to have the shifts automatically handled by prior instructions to the machine. From the experience at Electric Boat Division with the IBM 650 type machine, as applied to thermal stress calculations, the writer is inclined to believe that programs of successive load applications can be handled more or less automatically by a machine of this character. The paper has indicated that the handling of complications such as intermediate hangers can best be accomplished by maintaining a rather broad main routine which algebraically will be almost universal for all pipe lines. To these individual, standardized subroutines can be linked in the individual programming phases.

The problem of iteration for normal mode values is algebraically almost identical to that of the uniaxial problem. And the latter has a considerable computation history. This is a rather ideal technique for the digital class of computers and should pose few problems.

The other algebra pertaining to forced motions is rather routine and well within the capacities of intermediate type computers with little in the way of programming difficulty.

*Probability in Shock Analysis*

Probability considerations are important in almost all engineering work. It is clear that this is somewhat magnified in the case of shock. It commences with what can reasonably be expected in the way of stimulus. The predictability of the time history, say, of the supports for a pipe line requires considerable speculation. We have noted that the probability of compounding maximum amplitudes at various resonant frequencies is of considerable importance in this problem. And for this one would have to place much of his attention to quasi-statistical analysis of experimental data. In shock work we can be excessively conservative, and probability studies should be well worthwhile.

*Partially Plastic Action Shock*

Piping systems possess good properties in general for elastic energy storage, so important to good shock performance. Localized and slight yielding can increase this capacity considerably. This makes yielding a subject worth continued investigation. It is beyond the scope of this paper to go into this matter in any detail; a few notes on possible approaches may not be out of place.

(i) *Plastic Hinge Concept*

This notion has had a rather successful history in beam and frame analyses where bending occurs throughout in a single plane. And there is some experimental evidence to support it. The tacit assumption is that for any cross section the plot of bending moment versus rotation can be taken as the construct of a sloping straight line (the elastic portion) and a horizontal line (the plastic portion). With this it would follow that when yielding in bending commenced, there could be no further bending resistance at this section and that for all further loading of the system the section would in effect constitute a mechanical hinge for unconstrained rotation. The above plot is somewhat less realistic for piping than for normal beams and frames due to greater distribution of material out from the neutral axis. Also in almost all pipe systems the bending is not co-planar, and the bending moment at any section is really a vector quantity. In theory this vector could rotate with time after yielding, but for a short interval we might postulate a universal joint action for further load applications. The model we could make then would be of a reduced elastic system (with 'hinge') which is also susceptible to elastic analyses with new normal mode patterns etc. In these and other approaches a good model of the time history of the exciting forces or motions is needed.

(ii) *Integration with Respect to Time*

Newmark (16) has studied the motions of multi-storied rigid frames and the like from a somewhat different point of view. In effect, he predicts the time history of his structure step by step in time, each time utilizing the terminal values of displacement, velocity, etc. of the last step in estimating median values of acceleration for the next interval of time. In theory the process is equally applicable to elastic and plastic performance with stress-strain curves in hand. A certain amount of trial-and-error work is involved even in the choice of each succeeding time interval which is a critical element in the technique. The need for human kinds of judgment actions throughout the process is an obvious handicap to any application where machine computation is needed.

Nevertheless, some sort of stepwise construction of predicted time history is an attractive concept in cases where plastic action must be forecast. The paragraph (i) above suggests that elastic analyses of the original structure of the type shown herein could predict the time at which the modified elastic structure with 'hinge' would come into being. For the next interval of time the modified structure could be analyzed similarly with its new properties, and so forth. One criterion for complete collapse would be a subsequent structural modification to a structure which is unstable as a linkage.

The actual feasibility of this type of approach, of course, requires sharp scrutiny.

(iii) *Kinematical Linkage Study*

It is clear that there could be cases where the plastic deformations of a pipe line could so dominate that the elastic action would be insignificant. The problem could then take on a completely different form. Under these circumstances the pipe run might be analyzed as an array of rigid links joined by hinge-like connections caused by the plastic action. The examination would follow the lines of that for any mechanical linkage system with the notable exception that hinges would form and even move around with time. References (7) and (17) are illustrative of this approach as applied to more simple geometries.

*Use of Analogies*

The use of electrical analog computers has often been recommended for shock studies. There is much attraction to the notion especially as it has to do with time history predictions with various types of transient stimuli. It is also good for examining systematic design variations. Mr. R. E. Blake has noted to the writer in private correspondence that a 'pure' array of n elastically connected masses in space is analogous to a '3n' degree of freedom system* in uniaxial motion which *can* be electrically simulated once the influence coefficients have been established. The imposition of geometrical constraints, such as axial rigidity, and the need for proper directionality for the exciting stimuli pose some problems here. Also the evaluation of integrals, such as those of equations (73), as functions of time can be accomplished by observation of transients applied to suitable circuits. Analog computation is best suited to elastic study.

*Use of Models*

For a thorough knowledge of elastic and dynamic properties the use of small scale models of piping systems may not be an economy as a routine practice, owing to scaling problems, end conditions etc. It *is* possible that the determination of influence coefficients with static models might actually be an economy of itself. But as research vehicles models do offer promise. In association with shock test equipment, for example. the study of probabilities by model is attractive. The confirmation of modal patterns by model is certainly worthwhile.

*Combined Effect of Equipment and Piping*

There are certainly cases where the elastic performance of piping under dynamic loading can itself influence the motion of the equipment to which it is attached. In such cases the entire complex requires analysis. The attaching equipments are usually rigid bodies in the elastic sense with only a few degrees of freedom of themselves. The motions of same are unfortunately usually coupled. A study of this general class of problem following similar lines to the foregoing may be worthwhile.

*Failure Criteria*

The ability to contain its fluid is the major demand that is asked of a piping system. Stress analysis of

*If the masses lack significant rotational inertia.

the kind discussed here provides indices of this ability and measures of comparison between systems. The subject of failure itself falls to a different category which is less analytic and is cumbersome, and frustrating because of the strong influence of detail design practice. Its importance, nevertheless, suggests the definite need for investigatory work.

## VI CONCLUSION

This paper has repeatedly stated that piping system analysis, with all its geometric-algebraic clutter is in general little different from other structural analysis. Where analytical techniques have generally become well established, we should expect the inclusion of piping systems to be rather susceptible to similar practice, thanks to automatic computation. Where the problems in general are only partly understood, as in numerous subjects brought up in the last section, they are correspondingly difficult as applied to piping. There is this distinction to be drawn. In the field where analysis and/or test has become fairly routine there has grown up a body of talent with a strong sense of judgment and intuitive 'feel' for good practice. This is true of the linear-dynamic action of many structural classes; it is correspondingly true of thermal stresses of piping systems even where rather complex geometries are involved. It does not exist for the dynamic performance of piping systems. From this comes the designer's sense of proportion and fitness of the steps that he deems necessary. It is in pursuance of this quality, in particular, that further investigation of piping under dynamic loading is urged.

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## APPENDIX II SUMMARY OF OVERALL PROCEDURES

1. *Static Properties*
   (a) Geometric and Elastic Data Collection for Computer Routine. (Includes pertinent direction cosines at bends, designation of local reference axes and orientation with respect to principal axes of system, shape factors, etc.)
   (b) Selection of suitable lumped mass points.
   (c) Coefficients of redundants in expressions for moments and forces throughout reduced run.
   (d) Moments and forces attributable to unit load application in each of two directions as applied separately at n mass points, (including 'sway corner' and hanger load applications.)
   (e) Computation and tabulation of matrix of redundants' coefficients (integrations of partial derivatives) and constants—reduced pipe run.
   (f) Computations of deflection components of reduced run under unit load application in two directions and under unit redundant loads and moments at each mass point using data of (e). (Each load to be considered separately.)
   (g) Determination of redundants of reduced pipe run from (e), (for each unit force application.)
   (h) Determination of hanger reaction for each unit force application on true pipe run. (Equations of form (4)).
   (i) Determination of field moments and forces for each unit force application using formulations of (c), (d) and redundant data of (g) and (h).
   (j) Computation of deflection components (influence coefficients) of true pipe run using data of (f) and (h).

2. *Natural Frequencies and Normal Modes*

(a) Compute lumped mass values and total mass of leg (s) subject to axial sway, (including equivalent masses of sway corner (s) using (15)).

(b) Assume values for 'n' and 'p' components for first normal mode of free vibration, setting 'n' component at some $m_F$ equal to unity. ($\xi'_{j1}, \zeta'_{j1}$).

(c) Perform operations: [see (22)]

$$\begin{cases} N''_{k1} = M_k [\xi'_{j1}, \zeta'_{j1}] \\ P''_{k1} = N_k [\xi'_{j1}, \zeta'_{j1}]. \end{cases}$$

for all points $m_k$ using assumed values $\xi_{j1}, \zeta_{j1}$.

(d) Compute second approximations for first normal mode components:

$$\xi''_{k1} = N''_{k1} / N''_{F1}$$
$$\zeta''_{k1} = P''_{k1} / N''_{F1}.$$

(e) Successive repetitions of operations (c) and (d) until convergence on true first mode values appears satisfactory.

(f) Computation of first normal frequency:

$$\omega_1 = \sqrt{1/N'_{F1}}.$$

(g) Assumptions for successively higher modes using equations (27) and (28) to eliminate lower mode vestiges in assumptions. Otherwise operations are same as for first mode.

3. *Response of Pipe Run To Non-Uniform Shock*

(Problem of text involves uniform 'Z' direction motion of anchors A and E and oblique motion of hanger D.) (Summary below implies data given in the form of shock spectra in Z directions for A and E and in the X, Y and Z directions at D. Also maximum travel of points A, D, and E are given.)

(a) Computation of maximum relative excursion of hanger.

(b) Computation of reactions at D corresponding statically to the relative excursions of the hanger. (i.e. computation of coefficients of $n_D$, $p_D$, and $t_D$, using (32).

(c) Computation of equilibrium condition deflection components (i.e. coefficients of $n_D$, $p_D$, and $t_D$, ($A_{1k} \ldots\ldots B_{3k}$) in equations (34) for all $m_k$.

(d) Computation of coefficients, $C_{1k} \ldots$, $D_{1k} \ldots D_{4k}$ using (38) for all points $m_k$.

(e) Computation of $M_{1k}$, $M_{2k} \ldots\ldots N_{4k}$ of (56) for all points $m_k$.

(f) Computation of characteristic response parameters, $e_i$, $f_i$, $g_i$, and $h_i$ using (58) for selected number of lower frequencies, say, first three or four lowest modes.

(g) Estimate of limiting value of dynamic increment deflections using equations (76), with computed values of normal mode components, characteristic response parameters, and all shock spectrum values.

(h) Computations of limiting static deflection components using coefficients determined from (c) and equations (34).

(i) Computation of limiting values of total elastic deflection adding values of (g) and (h).

(j) Setup and solution of simultaneous set (79) for limiting inertial forces.

(k) Computation of limiting moments, forces and stresses using data from (h) and (j) and unit moments and forces from influence coefficient calculations.

## APPENDIX III SYMBOLS

$A_P$ — Cross sectional area of pipe material

$A_1', A_2', A_3'$ — Coefficients of $n_D$, $P_D$ and $t_D$ in expression (32) for $R_{nD}$.

$A_{1k}, A_{2k}, A_{3k}$ — Coefficients of $n_D$, $p_D$ and $t_D$ in expression (34) for $n_{ks}$.

$a$ — An arbitrary quantity

$\bar{a}_{ki}$ — Normal mode displacement vector for the kth mass point at the ith natural frequency of the system.

$a_i$ — The actual contribution of the ith normal mode shape in an assumed shape for any mode, r.

$$= \frac{\sum_{j=1}^{j=n} [m_{je}\, \xi_{ji}\, \xi'_{jr} + m_{je}'\, \zeta_{ji}\, \zeta'_{jr} + \Delta m_j (\zeta_{ji}\, \xi'_{jr} + \xi_{ji}\, \zeta'_{jr})]}{\sum_{j=1}^{j=n} [m_{je}\, \xi_{ji}^2 + m'_{je}\, \zeta_{ji}^2 + 2\Delta m_j\, \xi_{ji}\, \zeta_{ji}]}.$$

$B_1', B_2', B_3'$ — Coefficients of $n_D$, $p_D$ and $t_D$ in expression (32) for $R_{tD}$.

$B_{1k}, B_{2k}, B_{3k}$ — Coefficients of $n_D$, $p_D$ and $t_D$ in expression (34) for $p_{ks}$.

$b$ — An arbitrary quantity

$C_1', C_2', C_3'$ — Coefficients of $n_D$, $p_D$ and $t_D$ in expression (32) for $R_{tD}$.

$C_{1k}$ — Coefficient* of $\bar{X}_D$ in expression (37) for $\gamma_{ks}$

$C_{2k}$ — Coefficient of $\bar{Y}_D$ in expression (37) for $\gamma_{ks}$

$C_{3k}$ — Coefficient of $\bar{Z}_D$ in expression (37) for $\gamma_{ks}$

$C_{4k}$ — Coefficient of $\bar{Z}_A$ in expression (37) for $\gamma_{ks}$

$D_{1k}$ — Coefficient of $\bar{X}_D$ in expression (37) for $\chi_{ks}$

$D_{2k}$ — Coefficient of $\bar{Y}_D$ in expression (37) for $\chi_{ks}$

$D_{3k}$ — Coefficient of $\bar{Z}_D$ in expression (37) for $\chi_{ks}$

$D_{4k}$ — Coefficient of $\bar{Z}_A$ in expression (37) for $\chi_{ks}$

$E$ — Young's Modulus

$e_i$ — Characteristic Response parameter

$$\frac{\sum_{k=1}^{k=n} \{M_{1k} (m_{ke}\, \xi_{ki} + \Delta m_k\, \zeta_{ki}) + N_{1k} (m_{ke}'\, \zeta_{ki} + \Delta m_k\, \xi_{ki})\}}{\sum_{k=1}^{k=n} \{m_{ke}\, \xi_{ki}^2 + m_{ke}'\, \zeta_{ki}^2 + 2\Delta m_k\, \xi_{ki}\, \zeta_{ki}\}}$$

$f_i$ — Characteristic Response parameter (replace $M_{1k}$ and $N_{1k}$ in expression for $C_i$ with $M_{2k}$ and $N_{2k}$.

$F_j$ — A force (usually of magnitude-unity) at the jth mass

$F_{jn}, F_{jp}$ — Inertial forces in the n and p directions at the jth mass

*See equations (38) for evaluation of $C_{1k}$—$D_{4k}$.

$G$ Shear modulus

$g_i$ Characteristic response parameter (replace $M_{1k}$ and $N_{1k}$ in expression for $e_i$ by $M_{3k}$ and $N_{3k}$

$h_i$ Characteristic response parameter (replace $M_{1k}$ and $N_{1k}$ in expression for $e_i$ by $M_{4k}$ and $N_{4k}$

$I_X, I_P$ Flexural and polar moments of inertia of pipe cross section

$i$ Any mode of free vibration of the system

$$M_k[a,b] = \sum_{k=1}^{k=n}[(m_{je}\,\alpha_{kj}+\Delta m_j\,\bar{\alpha}_{kj})a + (m'_{je}\,\bar{\alpha}_{kj}+\Delta\bar{m}_j\,\alpha_{kj})b]$$

$M_{1k}=-M_k[C_{3k}, D_{3k}]$;
$M_{2k}=-M_k[C_{2k}, D_{2k}]$;
$M_{3k}=-M_k[C_{1k}, D_{1k}]$;
$M_{4k}=-M_k[C_{4k}, D_{4k}]$

$m_k, m_j$ Mass of arbitrary kth or jth mass

$m_{ke}=m_k$ for $k\neq B$ $\Delta m_k=0$ for $k\neq B$.
$=M_b\cos^2\Phi_B+m_k$ for $k\neq B$; $=M_b\cos\Phi_B:\cos\Psi_B$ for $k=B$.

$m_{ke}=m_k$ for $k\neq B$
$M_b\cos^2\Psi_B+m_k$ for $k=B$;

$m_F$ Selected point for normalizing all natural modes of vibration by setting $\xi_{Fi}=1.0$.

$$N_k[a,b] = \sum_{j=1}^{j=n}[(m_{je}\,\beta_k)+\Delta m_j\,\bar{\beta}_{kj})a + (m_{je}'\beta_{kj}+(m_{je}'\beta_{kj})b]$$

$N_{1k}=-N_k[C_{1k}, D_{1k})$;
$N_{2k}=-N_k[C_{2k}, D_{2k}]$;
$N_{3k}=-N_k[C_{3k}, D_{3k})$;
$N_{4k}=-N_k[C_{4k}, D_{4k}]$

$N_{ki}$ Result of (r-1) st iteration of assumed values of ith normal mode components with respect to components in n direction

$n_k$ Total elastic deflection in n direction

$n_{ks}$ Total elastic deflection in n direction corresponding to static equilibrium

$n_{ke}=n'_{ke}+n''_{ke}$ Elastic deflection in n direction due solely to inertial forces

$n'_{ke}$ Part of $n_{ke}$ due to accelerations, $\ddot{\gamma}_{js}$, $\ddot{\chi}_{js}$

$n''_{ke}$ Part of $n_{ke}$ due to accelerations, $\ddot{n}_{ke}$, $p_{ke}$

$n_D$ Displacement of D w/r to translated position in $n_d$ direction.

$n$ Local reference axis

$n$ Number of mass points by which the system is replaced in approximation

$P'_{ki}$ Result of (r-1)st iteration of assumed values of ith normal mode components with respect to components in the $p_d$ direction.

$P_E$ Reaction force at E in p direction for any unit load application

$p_k$ Total elastic deflection in p direction

$p_{ks}$ Total elastic deflection in p direction corresponding to static equilibrium

$p_{ke}=p'_{ke}+p''_{ke}$ Elastic deflection in p direction due solely to inertial forces

$P'_{ke}$ Part of $p_{ke}$ due to accelerations, $\ddot{\gamma}_{js}$, $\ddot{\chi}_{js}$

$P''_{ke}$ Part of $p_{ke}$ due to accelerations, $\ddot{n}_{ke}$, $\ddot{p}_{ke}$

$k=1.0$ For straight pipe } Correction factor in static flextural strain energy calculations
$=10+12(tR/r^2)^{-\frac{9}{2}}$ For bends }

$M_{nE}, M_{pE}, M_{tE}$ Moments at anchor E*

$M_b$ Total mass of leg b

$M_F$ Net flextural moment* at arbitrary pipe section

$M_T$ Net torsional moment* at arbitrary pipe section

$M_k[\ ]$ Operator symbol

$N_E$ Reaction force in $n_d$ direction at E for any unit load application

$(N_{Xi})_D, (N_{Yi})_D, (N_{Zi})_D$ Shock spectrum values for motion in X, Y, or Z directions at hanger location D. For example:

$$(N_{xi})_D=[\omega_i\int_0^t \ddot{X}_o \sin\omega_i(t-\tau)\,d\tau]_{max}$$

$(N_{Zi})_A$ Shock spectrum value for motion in Z direction at anchor locations A or E

$N_k[\ ]$ Operator symbol

$p_D$ Displacement of D in $p_D$ direction w/r to translated position

$Q_i(t)$ Generalized forcing function
$= \ddot{\bar{X}}_D\,e_i+\ddot{\bar{Y}}_D\,f_i+\ddot{\bar{Z}}_D\,g_i+\ddot{\bar{Z}}_A\cdot h_i$

$q_i(t)$ Generalized coordinate defining the ith mode contribution to the instantaneous elastic deflection. (Dynamic component)

$R$ Bend radius of pipe centerline

$r$ Mean radius of pipe metal

$r$ Number of iterations

$R_{nD}, R_{pD}, R_{tD}$ Reactions in $n_d$, $p_d$ and $-t_d$ directions at D due to any unit load application on system

$\bar{R}_{nD}, \bar{R}_{pD}, \bar{R}_{tD}$ Reactions in $n_d$, $P_d$ and $-t_d$ directions at D corresponding to the static equilibrium position

$T_E$ Reaction force at E in the $-t_d$ direction due to the application of any unit load on the system

$t$ Time—variable

$t$ Time at which deflection information is desired

$t$ Local reference axis

$t$ Pipe thickness (wall)

$t_D$ Displacement of D in $t_D$ direction w/r to translated position

$t_k$ Total elastic deflection in t direction

$t_{ks}$ Total elastic deflection in t direction corresponding to static equilibrium

$V$ Strain energy of system

$X, Y, Z$ Coordinate axes of system

$\bar{X}_D, \bar{Y}_D, \bar{Z}_D$ Instantaneous displacements of the hanger D in the X, Y, and Z directions

*If primes are used, they indicate properties for reduced pipe run without hanger.

| | |
|---|---|
| $\bar{\bar{Z}}_A$ | Instantaneous position of the anchors A and E in the Z direction |
| $\alpha_{kj}, \bar{\alpha}_{kj}, \bar{\bar{\alpha}}_{kj}$ | Influence coefficients—see separate tabulation |
| $\beta_{kj}, \bar{\beta}_{kj}, \bar{\bar{\beta}}_{kj}$ | Influence coefficients—see separate tabulation |
| $\gamma_{kj}, \bar{\gamma}_{kj}, \bar{\bar{\gamma}}_{kj}$ | Influence coefficients—see separate tabulation |
| $\kappa_{k1}=\kappa_{b1}$ | Tangential displacement amplitude (parallel to axis) of any point in leg b with system vibrating naturally at ith natural frequency, as normalized |
| $\phi, \Phi, \theta, \psi, \pi$, etc. | Geometrical angles of piping system—see Figure (1) |
| $\xi_{k1}, \zeta_{k1}$ | Normal mode components in local n and p directions. (Elastic displacement amplitudes for ith natural frequency) |
| $\xi_{k1}', \zeta_{k1}'$ | Tentative values of ith normal mode components. |
| $\omega$ | Any circular frequency |
| $\omega_i$ | The ith natural circular frequency |
| $\gamma_k, \chi_k, \delta_k$ | Displacements of $m_k$ in local n, p and t directions with respect to initial position—see Figure (6) |
| $\gamma_{ks}, \chi_{ks}, \delta_{ks}$ | Similarly defined displacements corresponding only to requirements of static equilibrium |
| $\tau$ | Any intermediate time between 0 and t |

*Influence Coefficients*—See Figures (1), (4)*

| | | | | | | |
|---|---|---|---|---|---|---|
| $\alpha_{kj}$ | Defl'n in | $n_k$† | dir'n at $m_k$ due to unit force in | $n_j$† | dir'n at | $m_j$ |
| $\bar{\alpha}_{kj}$ | Defl'n in | $n_k$ | dir'n at $m_k$ due to unit force in | $p_j$ | dir'n at | $m_j$ |
| $\bar{\bar{\alpha}}_{kj}$ | Defl'n in | $n_k$ | dir'n at $m_k$ due to unit force in | $t_j$ | dir'n at | $m_j$ |
| $\beta_{kj}$ | Defl'n in | $p_k$ | dir'n at $m_k$ due to unit force in | $n_j$ | dir'n at | $m_j$ |
| $\bar{\beta}_{kj}$ | Defl'n in | $p_k$ | dir'n at $m_k$ due to unit force in | $p_j$ | dir'n at | $m_j$ |
| $\bar{\bar{\beta}}_{kj}$ | Defl'n in | $p_k$ | dir'n at $m_k$ due to unit force in | $t_j$ | dir'n at | $m_j$ |
| $\gamma_{kj}$ | Defl'n in | $t_k$ | dir'n at $m_k$ due to unit force in | $n_j$ | dir'n at | $m_j$ |
| $\bar{\gamma}_{kj}$ | Defl'n in | $t_k$ | dir'n at $m_k$ due to unit force in | $p_j$ | dir'n at | $m_j$ |
| $\bar{\bar{\gamma}}_{kj}$ | Defl'n in | $t_k$ | dir'n at $m_k$ due to unit force in | $t_j$ | dir'n at | $m_j$ |

*Reciprocal Law*

$$\alpha_{kj}=\alpha_{jk};\ \bar{\alpha}_{kj}=\beta_{jk};\ \beta_{kj}=\bar{\alpha}_{jk};\ \bar{\bar{\beta}}_{kj}=\bar{\bar{\beta}}_{jk}$$
$$\bar{\bar{\alpha}}_{kj}=\gamma_{jk};\ \bar{\bar{\beta}}_{kj}=\gamma_{jk};\ \gamma_{kj}=\bar{\alpha}_{jk};\ \bar{\bar{\gamma}}_{kj}=\bar{\bar{\gamma}}_{jk}$$

## APPENDIX IV CONVERGENCE OF NORMAL MODE ITERATIONS

We have stated that any general elastic curve relative to the support configuration of the structure can be considered to be the vector sum of 2n other curves each of which is geometrically similar to one of the 2n normal mode patterns of free vibrations. We have standardized the latter type of curve as the possible form taken by the pipe run when vibrating freely at the corresponding frequency when the 'n' component of deflection amplitude is unity at some standardized point, $m_F$. The n and p components of the resultant normal mode vector at any point are defined $\xi_{k1}$ and $\zeta_{k1}$. To say that any elastic curve is the vector sum of curves geometrically similar to those defined by $\xi_{k1}$ and $\zeta_{k1}$, is to say that, this general curve can be defined by factors, say $a_1', a_2' \ldots a_i', a_{2n}'$ each of which when multipled by all $\xi_{k1}$, $\zeta_{ki}$ defines the *actual* contributing curve which is geometrically similar to the its normal mode shape. The general curve could be defined by vectors at all points, themselves the sum of the component vectors:

$$(83)\quad a_1'\vec{a}_{k1}+a_2'\vec{a}_{k2}+\ldots\ldots+a_1'\vec{a}_{k1}+\ldots\ldots+a_{2n}'\vec{a}_{k,2n}$$

with components:

$$(84)\quad \begin{cases} a_1'\xi_{k1}+a_2'\xi_{k2}+\ldots\ldots\ldots+a_i'\xi_{ki}+\ldots\ldots\ldots+a_{2n}'\xi_{k,2n} \\ +a_1'\zeta_{k1}+a_2'\zeta_{k2}+\ldots\ldots\ldots+a_i'\zeta_{ki}+\ldots\ldots\ldots+a_{2n}'\zeta_{k,2n} \end{cases}$$

Any assumed value for, say, the lowest natural mode of vibration is in fact just such a curve in space which we can define by the assumed component $\xi'_{k1}$ and $\zeta'_{k1}$. Let us say that these are represented by the series of the first and second of expressions (84) respectively. Now if we were to perform the following operations on these assumed values:

$$(85)\quad \left.\begin{matrix} N_{k1}''=M_k[\xi_{j1}', \zeta_{j1}'] \\ P_{k1}''=N_k[\xi_{j1}', \zeta_{j1}'] \end{matrix}\right\}\ \text{See eq. (22) for operators } M_k[\ ], N_k[\ ],$$

we actually have from (84) a breakdown of operations as follows:

$$(86)\quad \begin{cases} N_{k1}''=M_k[a_1'\xi_{j1}, a_1'\zeta_{j1}]+M_k[a_2'\xi_{j2}, a_2'\zeta_{j2}]+\ldots\ldots \\ P_{k1}''=N_k[a_1'\xi_{j1}, a_1'\zeta_{j1}]+N_k[a_2'\xi_{j2}, a_2'\zeta_{j2}]+\ldots\ldots \end{cases}$$

or

$$(87)\quad \begin{cases} N_{k1}''=a_1'\cdot M_k[\xi_{j1}, \zeta_{j1}]+a_2'\cdot M_k[\xi_{j2}, \zeta_{j2}]+\ldots\ldots \\ P_{k1}''=a_1'\cdot N_k[\xi_{j1}, \zeta_{j1}]+a_2'\cdot N_k[\xi_{j2}, \zeta_{j2}]+\ldots\ldots \end{cases}$$

But the general equations (21) of the text show that the terms $M_k[\xi_{j1}, \zeta_{j1}]$ and $N_k[\xi_{j1}, \zeta_{j1}]$ are actually equal to $\xi_{k1}/\omega_1^2$ and $\zeta_{j1}/\omega_1^2$. Similarly $M_k[\xi_{j2}, \zeta_{j2}]$ and $N_k[\xi_{j2}, \zeta_{j2}]$ are equal to $\xi_{k2}/\omega_2^2$ and $\zeta_{k2}/\omega_2^2$, and so forth. Thus the operation (87) gives:

$$(88)\quad \begin{cases} N_{k1}''=\dfrac{a_1'\xi_{k1}}{\omega_1^2}+\dfrac{a_2'\xi_{k2}}{\omega_2^2}+\dfrac{a_3'\xi_{k3}}{\omega_3^2}+\ldots\ldots\ldots\ldots \\ P_{k1}''=\dfrac{a_1'\zeta_{k1}}{\omega_1^2}+\dfrac{a_2'\zeta_{k2}}{\omega_2^2}+\dfrac{a_3'\zeta_{k3}}{\omega_3^2}+\ldots\ldots\ldots\ldots \end{cases}$$

The new pair, $N_{k1}''$ and $P_{k1}''$ define a new curve of the structure in space. A geometrically similar curve is defined by $N_{k1}''/N_{F1}''=\xi_{k1}''$ and $P_{k1}''/N_{F1}''=\zeta_{k1}''$. The latter curve is normalized as was the originally assumed shape $\xi_{k1}'$ and $\zeta_{k1}'$. The new curve, as normalized, is expressible:

*Primes on influence coefficients indicate values for reduced pipe run without hanger.

†The subscripts for 'n' and 'p' refer to the local reference axes of the pipe leg in which $m_k$ or $m_j$ is situated.

$$(89)\quad \begin{cases} \xi_{k1}'' = \dfrac{1}{N_{F1}''}\left[\dfrac{a_1'}{\omega_1^2}\xi_{k1} + \dfrac{a_2'}{\omega_2^2}\xi_{k2} + \cdots\cdots\right] \\ \zeta_{k1}'' = \dfrac{1}{N_{F1}''}\left[\dfrac{a_1'}{\omega_1^2}\zeta_{k1} + \dfrac{a_2'}{\omega_2^2}\zeta_{k2} + \cdots\cdots\right] \end{cases}$$

If we compare equation (89) with the original counterpart, (84), we note that the original ratio between the first and second terms of (84) was $a_2'/a_1'$. But in the pair (89) the corresponding ratio is $\left(\frac{\omega_1}{\omega_2}\right)^2 \cdot \frac{a_2'}{a_1'}$. But, by definition, $\omega_2 > \omega_1$, and therefore the contribution of the second mode shape with respect to the first is less in the new curve. The same can be demonstrated for all the higher modes, the decrease in contribution being successively greater mode by mode. A repeated operation $M_k[\xi_{k1}'', \zeta_{k1}'']$, $N_k[\xi_{k1}'', \zeta_{k1}'']$ followed by renormalizing would show the same trend with respect to the second trial. This, then, demonstrates that successive trials will converge upon the lowest, fundamental mode. Graphically what is happening during the iteration processes is that the originally assumed vectors of displacement are being rotated and expanded or contracted until in the limit they swing into coincidence with the true first mode vectors at each point.

A curve which contained contributions of all but the first mode could be shown similarly to converge on the second mode and so forth. It is possible to take an assumed curve such as (84) and, knowing the values of $\xi_{k1}'$ and $\zeta_{k1}'$, to remove the vestiges $a_1'\xi_{k1}$, $a_1'\zeta_{k1}$ of the first mode characteristic. This can be acccomplished by computing the value $a_1'$ in (84). First we rewrite (84) as an assumed shape of the *second* mode:

$$(84A)\quad \begin{cases} \xi_{k2}' = \sum_{i=1}^{i=2n} a_{k1}'\xi_{k1} \\ \zeta_{k2}' = \sum_{i=1}^{i=2n} a_{k1}'\zeta_{ki} \end{cases}$$

and multiply the first expression of (84A) by $(m_{ke}\xi_{k1} + \Delta m_k \zeta_{k1})$ and the second by $(m_{ke}'\zeta_{k1} + \Delta m_k \cdot \xi_{k1})$. We then sum the results over all mass points, $m_k$, and add the two with the result:

$$(90)\quad \sum_{k=1}^{k=n}[m_{ke}\xi_{k1}\xi_{k2}' + m_{ke}'\zeta_{k1}\zeta_{k2}' + \Delta m_k(\zeta_{k1}\xi_{k2}' + \xi_{k1}\zeta_{k1})]$$
$$= a_1' \sum_{k=1}^{k=n}(m_{ke}\xi_{k1}^2 + m_{ke}'\zeta_{k1}^2 + 2\Delta m_k\xi_{k1}\zeta_{k1})$$
$$+ a_2' \sum_{k=1}^{k=n}[m_{ke}\xi_{k1}\xi_{k2} + m_{ke}'\zeta_{k1}\zeta_{k2} + \Delta m_k(\zeta_{k1}\xi_{k2} + \xi_{k1}\zeta_{k2})]$$
$$+ \cdots\cdots\cdots\cdots$$
$$+ \cdots\cdots\cdots\cdots$$

In the following appendix it is shown that for any mode $p \neq i$:

$$(29)\quad \sum_{k=1}^{k=n}[m_{ke}\xi_{ki}\xi_{kp} + m_{ke}'\zeta_{ki}\zeta_{kp} + \Delta m_k(\xi_{ki}\zeta_{kp} + \zeta_{ki}\xi_{kp}) = 0,$$

which is the orthogonality condition for this type of structure. This means that all sums on the right hand side of (90) save the first must vanish identically. The resulting equation contains terms which are all known except $a_1'$, and is therefore expressible:

$$(91)\quad a_1' = \frac{\sum_{k=1}^{k=n}[m_{ke}\xi_{k1}\xi_{k2}' + m_{ke}'\zeta_{k1}\zeta_{k2}' + \Delta m_k(\zeta_{k1}\xi_{k2}' + \xi_{k1}\zeta_{k2}')]}{\sum_{k=1}^{k=n}(m_{ke}\xi_{k1}^2 + m_{ke}'\zeta_{k1}^2 + 2\Delta m_k\xi_{k1}\zeta_{k1})}.$$

## APPENDIX V ORTHOGONALITY RELATIONSHIP

The basic relationships between the normal mode components which were developed in the text are:

$$(20)\quad \text{(a)}\ \xi_{ki} = \omega_i^2 \sum_{j=1}^{j=n}\{(m_{je}\alpha_{kj} + \Delta m_j\bar{\alpha}_{kj})\xi_{ji} + (m_{je}'\bar{\alpha}_{kj} + \Delta m_j\alpha_{kj})\zeta_{ji}\}$$
$$\text{(b)}\ \zeta_{ki} = \omega_i^2 \sum_{j=1}^{j=n}\{(m_{je}\beta_{kj} + \Delta m_j\bar{\beta}_{kj})\xi_{ji} + (m_{je}'\bar{\beta}_{kj} + \Delta m_j\beta_{kj})\zeta_{ji}\}.$$

If we were to multiply each side of (20a) by $m_k\xi_{kp}$, where $p \neq i$, and then were to sum over all $m_k$, we could rearrange certain terms on the right hand side of the resulting equations, recalling also the reciprocal relationships (1) of the influence coefficients (i.e. $\alpha_{kj} = \alpha_{jk}$; $\alpha_{kj} = \beta_{jk}$; etc.), and the resulting equation would be:

$$(92)\quad \sum_{k=1}^{k=n} m_{ke}\xi_{kp}\xi_{ki} = \omega_i^2\left\{\sum_{j=1}^{j=n} m_{je}\xi_{ji}\sum_{k=1}^{k=n} m_{ke}\xi_{kp}\alpha_{jk} + \sum_{j=1}^{j=n}\Delta m_j\xi_{ji}\sum_{k=1}^{k=n} m_{ke}\xi_{kp}\beta_{jk}\right.$$
$$\left. + \sum_{j=1}^{j=n} m_{je}'\zeta_{ji}\sum_{k=1}^{k=n} m_{ke}\xi_{kp}\beta_{jk} + \sum_{j=1}^{j=n}\Delta m_j\zeta_{ji}\sum_{k=1}^{k=n} m_{ke}\xi_{kp}\alpha_{jk}\right\}.$$

Now for each term on the right hand side of this equation the second summation is actually a part of the normal mode component divided by $\omega_p^2$. For example, we can designate $\sum_{k=1}^{k=n} m_{ke}\xi_{kp}\alpha_{jk} = (\xi_{jp})_n{}^m/\omega_p^2$ where we can imply that the term $(\xi_{jp})_n{}^m$ is that part of $\xi_{jp}$ which is caused solely by the inertial forces $-m_k\ddot{\xi}_{kp}$ (acting in the local n directions). As another example: the term $(\xi_{jp})_p{}^{m'}$ implies the part of $\xi_{jp}$ caused by the inertial forces $(-m_{ke}'\cdot\ddot{\zeta}_{kp}$ operating in the local p directions). Thus (92) can be written:

$$(93)\quad \sum_{k=1}^{k=n} m_{ke}\xi_{kp}\xi_{ki} = \frac{\omega_i^2}{\omega_p^2}\left\{\sum_{j=1}^{j=n}[m_{je}\xi_{ji}(\xi_{jp})_n{}^m + \Delta m_j\xi_{ji}(\zeta_{jp})_n{}^m + m_{je}'\zeta_{ji}(\zeta_{jp})_n{}^m + \Delta m_j\zeta_{ji}(\xi_{jp})_n{}^m]\right\}.$$

By entirely reasoning if we multiplied (20b) by $m_{ke}'\zeta_{kp}$ and summed up over all $m_k$ we would turn up with

$$(94)\quad \sum_{k=1}^{k=n} m_{ke}'\zeta_{ki}\zeta_{ki} = \frac{\omega_i^2}{\omega_p^2}\left\{\sum_{j=1}^{j=n}[m_{je}\xi_{ji}(\xi_{jp})_p{}^{m'} + \Delta m_j\xi_{ji}(\zeta_{jp})_p{}^{m'} + m_{je}'\zeta_{ji}(\zeta_{jp})_p{}^{m'} + \Delta m_j\zeta_{ji}(\xi_{jp})_p{}^{m'}]\right\}$$

On the other hand, had we multiplied (20a) and (20b) by $\Delta m_k\zeta_{kp}$ and $\Delta m_k\xi_{kp}$ respectively and similarly summed, the two resulting equations with the same symbolic form would be:

$$(95)\quad \sum_{k=1}^{k=n}\Delta m_k\zeta_{kp}\xi_{ki} = \frac{\omega_i^2}{\omega_p^2}\left\{\sum_{j=1}^{j=n}[m_{je}\xi_{ji}(\xi_{jp})_n{}^{\Delta m} + \Delta m_j\xi_{ji}(\xi_{jp})_n{}^{\Delta m} + m_{je}'\zeta_{ji}(\zeta_{jp})_n{}^{\Delta m}\Delta m_j\ \zeta_{ji}(\xi_{jp})_p{}^{\Delta m}]\right\}$$

$$(96)\quad \sum_{k=1}^{k=n}\Delta m_k\xi_{kp}\zeta_{ki} = \frac{\omega_i^2}{\omega_p^2}\left\{\sum_{j=1}^{j=n}[m_{je}\xi_{ji}(\xi_{jp})_p{}^{\Delta m} + \Delta m_j\xi_{ji}(\zeta_{jp})_p{}^{\Delta m} + m_{je}'\zeta_{ji}(\zeta_{jp})_p{}^{\Delta m} + \Delta m_j\zeta_{ji}(\xi_{jp})_p{}^{\Delta m}]\right\}.$$

If we were now to add equations (93)-(96), there would be terms such as $m_{je}\xi_{ji}[(\xi_{jp})_n{}^m + (\xi_{jp})_p{}^{m'} + (\xi_{jp})_n{}^{\Delta m} + (\xi_{jp})_p{}^{\Delta m}]$. But this quantity in brackets [ ] is simply $\xi_{jp}$ since this accounts for all the inertial forces which cause the deflection $\xi_{jp}$. This type of contraction can be made for all terms in the proposed summation of equations (93)-(96). The net result of this would be then:

$$(97)\quad \sum_{k=1}^{k=n}[m_{ke}\xi_{kp}\xi_{ki} + m_{ke}'\zeta_{kp}\zeta_{ki} + \Delta m_k(\zeta_{kp}\xi_{ki} + \xi_{kp}\zeta_{ki})] = \frac{\omega_i^2}{\omega_p^2}\sum_{j=1}^{j=n}[m_{je}\xi_{jp}\xi_{ji} + m_{je}'\zeta_{jp}\zeta_{ji} + \Delta m_j\ (\zeta_{jp}\xi_{ji} + \xi_{jp}\zeta_{ji})].$$

Now, of course, a summation over all k is equivalent to a summation over all j since $m_k$ and $m_j$ are entirely arbitrary. The obvious meaning of (97), $(1-\omega_i^2/\omega_p^2)$ being constant and non-zero, is that for $p \neq i$:

$$(29)\quad \sum_{j=1}^{j=n}[m_{je}\xi_{ji}\xi_{jp} + m_{je}'\zeta_{ji}\zeta_{jp} + \Delta m_j\ (\xi_{ji}\zeta_{jp} + \zeta_{ji}\xi_{jp})] = 0.$$

And (29) expresses the orthogonality property of this class of structure which is of such powerful assistance to the formulations developed here.

It can also be noted that when p=i;

$$(29a)\quad \sum_{j=1}^{j=n}[m_{je}\xi_{ji}{}^2 + m_{je}'\zeta_{ji}{}^2 + 2\Delta m_j\ (\xi_{ji}\zeta_{ji})] = \text{CONSTANT}.$$

## APPENDIX VI CHARACTERISTIC RESPONSE PARAMETERS

In discussing shock we discovered that after having evaluated certain quantities, $M_{1k}-M_{4k}$, and $N_{1k}-N_{4k}$, these terms could be expressible in normal mode terms. For example, the pair, $M_{1k}$ and $N_{1k}$, were expressed:

$$(57a)\quad \begin{cases} M_{1k} = \sum_{i=1}^{i=2n} e_i\ \xi_{ki} \\ N_{1k} = \sum_{i=1}^{i=2n} e_i\ \zeta_{ki}. \end{cases}$$

These values, $M_{1k}$ and $N_{1k}$, correspond (from (56)) to the deflections caused by part of the inertial forces; $-m_j\ddot{y}_{js}, -m_j\ddot{\chi}_{js}$, under the circumstances that $\ddot{\chi}_D = 1.0$, and $e_i$ is the generalized coordinate describing the ith contribution to such a curve. These equations (57a) are actually simultaneous and solvable, when written for all k, and for all i. But, as has been noted, there is an easier approach.

We could multiply the equations (57a) by $(m_{ke}\xi_{kp} + \Delta m_k\zeta_{kp})$ and $(m_{ke}'\zeta_{kp} + \Delta m_k\zeta_{kp})$ respectively and in each case sum over all points $m_k$ yielding:

$$(98)\quad \sum_{k=1}^{k=n} M_{1k}[m_{ke}\xi_{kp} + \Delta m_k\zeta_{kp}] = \sum_{i=1}^{i=2n} e_i \sum_{k=1}^{k=n}(m_{ke}\xi_{kp} + \Delta m_k\zeta_{kp})\xi_{ki}$$

$$(99)\quad \sum_{k=1}^{k=n} N_{1k}[m_{ke}'\zeta_{kp} + \Delta m_k\xi_{kp}] = \sum_{i=1}^{i=2n} e_i \sum_{k=1}^{k=n}(m_{ke}'\zeta_{kp} + \Delta m_k\xi_{kp})\zeta_{ki}.$$

Now if we add (98) and (99) we find that all terms on the right hand side of the resulting equation vanish except when i=p by virtue of the orthogonality relationship (29). Another way of saying this is to assert that the summations of all i in (98) and (99) contract to the single terms where i=p only. There is only one variable, $e_1$, that is unknown in the resulting combined equation. And this permits the evaluation:

$$(58)\quad e_1 = \frac{\sum_{k=1}^{k=n} \{ M_{1k} (m_{ke}\xi_{k1} + \Delta m_k \zeta_{k1}) + N_{1k} (m_{ke}'\zeta_{k1} + \Delta m_{ke}\xi_{k1}) \}}{\sum_{k=1}^{k=n} \{ m_{ke}\xi_{k1}^2 + m_k'\zeta_{k1}^2 + 2\Delta m_k \xi_{k1} \cdot \zeta_{k1} \}}.$$

The other parameters, $f_1$ $g_1$ and $h_1$ can be similarly evaluated by the identical reasoning.

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# SOME SAFETY ASPECTS OF OFFSHORE GEOPHYSICAL OPERATIONS FROM THE EQUIPMENT PERSPECTIVE

**THE AUTHOR**

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In all probability no one phase of American industry is subject to as many governing bodies and their regulations as is the maritime industry. The governing bodies and their control over the maritime industry also include the same bodies and regulations that govern the small boat industry and, more particularly, the offshore oil operator and the offshore geophysical explorer. The basic objectives of these bodies are safety to equipment and to the seafaring personnel. Whether these objectives are efficiently and economically executed is not the aim of the author in this paper, but it must be agreed that the principles on which these regulatory bodies are founded are legally and morally sound, and have contributed materially to the safety of those who go to sea for a livelihood.

Looking into the history of safety in our maritime trade, one can go back to 1832 when 14 per cent of the vessels in operation were destroyed by explosions and fires, and the loss of life was approximately 1000. In 1871, after years of failure to incorporate effective legislation, the Bureau of Steamboat Inspection was created; and although it did not attain the ideal sought, it was effective in reducing the yearly toll of life to 245, as compared with previous yearly averages of 700.[8][1] Through the many changes in the functions and organization of the various departments of our government, the Bureau of Steamboat Inspection finally became the Marine Inspection Office of the United States Coast Guard under the reorganization transferring it from the Department of Commerce to the Treasury Department.

Representative of the scope of the governmental agencies responsible for the legal aspect of securing conformity with recoginzed standards in the business of building and operating ships is the following list of human and technical requirements for which the U. S. Coast Guard is responsible: [8]

[1]Numbers in parentheses refer to the Bibliography at the end of the paper.

*Human Requirements*

(Assurance of competent and adequate personnel.)

1. Examination for licensing and certificating personnel.
2. Determination of a vessel's necessary complement of personnel.
3. Minimum age requirements.
4. Disciplinary measures for seafaring personnel.

*Technical Requirements*

(Legal standards for the construction and operation of ships.)

1. Structural strength of ships.
2. Subdivision and stability of ships.
3. Load-line requirements.
4. General rules as to machinery of ships.
5. Protection against fire hazards (including tanker regulations).
6. General requirements for life-saving equipment.
7. Rules on communication systems at sea (including those on board, between ships, and ships-to-shore).
8. Federal regulations of motorboats.
9. Legal requirements of the International Convention for the Safety of Life at Sea, 1948.

Under the supervision of the U. S. Coast Guard and of the American Bureau of Shipping, a workable system of safeguarding the traveling public, the insurance underwriter, the shipowner, and the shipbuilder has been evolved. The American Bureau of Shipping publishes Rules for Building and Classing Steel Vessels, and a record giving particulars of vessels classed and their ratings. It is authorized to assign load lines under the provisions of the U. S. Load Line Acts of 1929 and 1935.

The foregoing brief of the functions and responsibilities of the regulatory bodies is intended to give some idea of the scope of activity that has been undertaken by the government to insure that safety of life and equipment at sea is put into effect and enforced. Not all of the aforementioned requirements are applicable to the operation of a geophysical party offshore. Some of the regulations are not applicable because of the basic characteristics of the vessel; or they can be avoided by placing the vessel in a category according to its length, gross tonnage, service, type of propulsion, limited trade routes, etc. Nevertheless, under the jurisdiction of the U. S. Coast Guard there are regulations which will govern the construction and certification of all floating equipment; and although attempts to evade these regulations are often made on mere points of technicaltiy, the moral responsibility finally rests with the owner or operator should a disaster occur.

The "Motorboat Regulations" administered by the Coast Guard require nothing more than compliance with certain regulations concerning navigation lights, fire extinguishers, and life jackets, life rings or life preservers, and apply to all motor boats and motor vessels not subject to inspection and certification.

As a matter of information, just recently the entire set of Rules and Regulations for Vessel Inspection underwent a complete revision; public hearings were conducted where the shipbuilders, owners, operators, naval architects, etc., had an opportunity to request changes in the proposed legislation which would benefit the trade. The rules and regulations for the inspection of all types of vessels were revised for the principal reason of incorporating therein requirements made necessary as a result of the United States being a signatory body to the International Convention for the Safety of Life at Sea, 1948. The effective date of the provisions of the Convention was November 19, 1952. Vessels were required to be in conformance within one year from that date.

Because the shipbuilder does not build ships for his own account, his concern with the numerous laws, rules, and regulations is not primarily cost. When he puts in his bid, he usually has specifications calling for design, material, equipment, and workmanship in accordance with the requirements of certain regulatory bodies. He is supposedly familiar with these requirements, includes the cost in his bid, and thus passes it on to the owner. It does not follow, therefore, that the builder welcomes unlimited rules calling for more equipment and finer workmanship in order to make a bigger and more expensive job. After all, there is the possibility that the cost may become excessive so that the owner will decide not to build; and, even though the owner pays the bill, he is the shipbuilder's best customer so naturally the builder has the owner's interests in mind at all times.[7]

When a vessel is constructed, compliance with the requirements of the following is usually written into the specifications or incorporated by reference:[7]

1. American Bureau of Shipping
2. United States Coast Guard
3. Revised Statutes, Navigation Laws of the United States
4. International Load Line Convention, London, 1930
5. International Convention for the Safety of Life at Sea, 1948
6. United States Public Health Service
7. Senate Report No. 184
8. Federal Communications Commission Radio
9. United States Customs Admeasurement
10. American Institute of Electrical Engineers Recommended Practice for Electrical Installation on Shipboard. (Now a part of Item 2)
11. All other applicable laws as required for procurement of necessary certification.

The rules and regulations that have been mentioned were designed to protect the individual, the partnership, and/or the corporation; but often there is someone who feels, like the fast driver on the highway, that these rules apply to "the other fella, not me" and proceeds on his merry way to place in commission a surplus craft of nondescript characteristics that was converted under ill-advised conditions. Some of the deficiencies these vessels may have are:

Insufficient initial stability or range of stability.

Improper fuel tank sounding facilities.

Improper fuel tank venting facilities, or the venting of fuel into a closed compartment.

Inadequate structural strength.

Defective electrical wiring and unprotected circuits.

Lack of bilge pumps or pumps of insufficient capacity to handle a damaged condition.

Inadequate watertight subdivisions and inefficient watertight closure appliances.

Fire fighting equipment that is either inefficient, inadequate, or aged beyond effective life.

Insufficient life-saving equipment in form of ring buoys or preservers.

This list is not intended to be a complete list of the deficiencies which might exist in a vessel; however, it does list some major ones which have caused vessel losses and which are existing in many vessels that are in service today. Many owners are now trusting to luck and are hoping that no ill fortune will happen until the vessel is idle and can be overhauled without a loss of working time.

The consequences of such expediencies is to endanger the lives of the operating crew and jeopardize the owner's investment in the facility. Compliance with the rules is actually a cheap form of insurance.

One author on safety[4] has listed fourteen major causes of accidents and has credited twelve of the fourteen causes as being due to the human factors involved. (It is imperative that physical fitness and a higher level of intelligence and training be required of seamen. Thousands of dollars are spent to design and make a vessel safe, only to be entrusted to inferior personnel.) The two material factors are defective equipment and unsafe structures. The major portion of the existing laws and regulations governing vessel inspection are primarily designed to minimize material and equipment failures, and to guarantee a safe structure within the limits of quality inspection.

In a geophysical shooting expedition, the knowledge that several thousand pounds of explosives are on board should naturally promote safety precautions in the handling of the explosives, their storage, and shipboard fire precautions. Certain types of explosives are set off by booster charges which are in turn primed by electrically charged detonators. A possible detonation exists if the electrical equipment and circuits are not properly grounded, since handling the detonators and explosives in contact with the vessel and its equipment may release a charge of sufficient capacity to set off the detonator. Aboard a wooden vessel this danger is magnified unless all current carrying equipment and materials are bonded together and carried to grounding plates on the vessel's submerged hull. A steel hull vessel is less difficult to ground. Grounding of all the electrical circuits and outlets will also prevent severe shocks or the electrocution of personnel due to the inherent dangers of ungrounded equipment, as well as eliminating the chances of a possible premature detonation.

Seaworthiness and stability are often given slight consideration when sending a vessel to sea, and sometimes it is left to the master seaman's "feel" of the vessel—a person who may or may not be qualified to exercise such judgment. The experienced seaman is often unqualified to predict the stability of a vessel in a seaway, even after being shipmates with the vessel for a considerable length of time. The fishing trade offers a wealth of information in this respect since fishing vessels generally are evolutions of types which have been in use over a long period of time. A fisherman stepping into a new boat, which is usually slightly modified from an existing type, has to decide by his senses whether the boat is safe or not. Does she heel too much when he puts the rudder hard over? Is she tender when she has a load of fish on deck? The fisherman uses his senses of feel to evaluate these points. To give him his due, he has generally been right in his decisions, and the number of casualties in fishing vessels due to an insufficient margin of stability is relatively low.[11]

Seaworthiness describes the fitness of a vessel with respect to the condition of its hull and machinery, the extent of its fuel and provisions, the quality of its officers and crew, and its adaptability for the proposed voyage.

The question of what constitutes a satisfactory margin of stability for a floating object is as old as the first floating structure and, up to comparatively recent times, it has been answered only empirically. Vessels which continued to go to sea and come back safely were judged to have a satisfactory margin of stability. Those which capsized and were lost had an inadequate margin.[11]

Stability, a prerequisite of seaworthiness, is a function of the vessel's hull form, freeboard, watertight subdivision, and the location of the center of gravity of the vessel, its cargo and all weights on board. The initial stability or metacentric radius of a vessel is a criterion by which the stability of a vessel is measured, but this criterion is not to be considered all-inclusive since it is applicable only for the angles of inclination of the vessel where the angle of heel does not exceed 7 to 10 degrees. Outside of this initial range, the stability becomes an involved calculation including many variables and, because of the complexities involved, the vast majority of floating structures in the world today are built without any analysis of stability other than the old empirical question: "Has it turned over yet?" The naval architect is best qualified to predict the range of stability of a vessel, and his qualifications are based upon his knowledge of the behavior of other vessels of similar form having a known initial metacentric radius; to wit, the engineering method of direct evaluation.

The converted vessel which has had weights removed, relocated, and added without a check calculation of the effect of these changes is a dangerous vessel to be afloat. Although the vessel may float upright and appear to have a sufficient righting moment for moderate angles of heel at the pier, she may capsize when subjected to the forces that are experienced in a seaway because the vessel's range of stability was seriously impaired during the conversion.

Stability is of such paramount importance to the vessels of the U. S. Navy that during repairs, overhauls, or modifications an accurate record is kept of the weights that are moved and their location vertically and fore and aft, so that the location of the vessel's center of gravity can be determined, and thus determine the effect of the changes on the vessel's stability characteristics.

Having selected the proper vessel and incorporated therein the necessary safety features that are based upon the experience and personal preferences of the architect, builder, owner and operator, it then be-

comes the responsibility of the personnel on board to indoctrinate safe practices that will minimize the elements of human responsibility.

Safety at sea results from a combination of wide experience and technical ability of naval architects and boat builders to design, lay down, construct, and equip a good ship; but it is not effective unless the vessel is manned by competent officers and crew.

Many of the vessels that are employed in the offshore oil industry are not required either by a federal or independent agency to establish and certify the qualifications for the seagoing personnel that will man these boats, and in this era of labor shortages and union influence everyone cognizant of the meaning of the word "seamanship" will admit the incompetence of the crews and their inattention to duty.

A serious error of judgment occurs when a vessel stays out beyond the safe period of operation when treacherous weather is expected. This error can be attributed to faulty instructions, the inability of the employee, the lack of concentration, or the permitting of an unsafe practice. With today's method of reporting and tracking down local and tropical disturbances, there is little or no excuse for a vessel overstaying its welcome when bad weather is pending. Many of the vessels engaged in offshore work are of insufficient size to weather through a moderate blow without damage to the vessel or injury to the personnel on board. Furthermore, it is impossible to conduct operations of any sort when the weather is bad, as the main consideration of all on board is self-survival. To expose personnel and equipment to such risk is a foolhardy attempt at false economy. One mishap can cost in prestige to a company and its operations far more than the lost time of returning to a safe harborage to wait out a blow. Once exposed to the fury of the elements, the only known procedure is to insure watertightness, pick the course and speed at which the boat will ride easiest, hang on for life, and make a prayer that will offer the best chance for survival.

Many of the features of a marine safety program have been omitted in this paper because space does not permit. Marine safety is a "watch in watch," "all hands evolution." Only a few of the elementary facets of marine safety have been mentioned, but it is the author's hope that the management of the companies engaged in offshore geophysical prospecting will become increasingly aware of offshore safety problems.

In conclusion, the author believes that the initial step in a safe program is for the owner or operator to consult a naval architect or a shipyard that is staffed with experienced personnel, who are most familiar with the problems and the requirements of the regulatory bodies and who have a wealth of data from the experience of building and operating many types of vessels. With this procedure a vessel owner or operator may save himself costly modifications, time, and embarrassment by having to comply at the last minute with a law relating to equipment or construction before the vessel is permitted to sail. A naval architect collects and records data on which to base the performance of his design in the same manner that a geophysicist will obtain and record accurate and detailed geophysical data that relates to an oil field, in order that he may predict the producing capabilities of the unknown area that is his next survey.

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# ALL-WELDED 96-FT AMERICAN-BUILT MOTOR YACHT

*This paper, presented at the 1955 National Fall Meeting of the American Welding Society, was published in the January, 1956, edition of "The Welding Journal." The authors are LaMotte Grover, of Air Reduction Sales Co., and E. H. Holder, of Ingalls Shipbuilding Corporation.*

## GENERAL DESCRIPTION

THE all-welded yacht, *Rhonda III* (Fig. 1), is of special interest to the welding industry as an example of the successful application of certain principles of design and construction, to control distortion and to suppress noise and vibration during operation.

The completion of this 96-ft twin-screw yacht in January 1955, by the Ingalls Shipyard at Pascagoula, Miss., adds a new and important chapter to the history of American motor-yacht design and construction. The vessel was designed by M. Rosenblatt and Son, New York Naval Architects and Marine Engineers, to meet requirements determined largely by Robert I. Ingalls, Jr., Chairman of the Ingalls Shipbuilding Corp. She is outstanding in her class for many of her features.

An important requirement was the ability to cruise at great distances off shore, despite a relatively shallow draft suitable for cruising in southern waters. She is capable of a 12½-knot sustained cruising speed and a maximum speed of 13 knots. Powered by two Diesel engines of 426 normal shaft horsepower each, with a 4940-gal fuel oil capacity, she has a cruising range of 2500 miles at a speed of 8½ knots. She is well insulated and completely air conditioned.

Many yacht builders and designers have contended that steel hull construction can be employed for pleasure craft only with a sacrifice in appearance or with excessive cementing to conceal warping, especially in the case of welded construction. There are others who have come to realize the advantages and merits of steel construction, but still maintain that objectionable noise and vibration can be eliminated in steel pleasure craft, only by the use of riveted joints. Some designers and builders advocate the use of strips of some kind of vibration-damping material, introduced between the faying surfaces of a riveted joint, to interrupt the continuity of the steel plating and prevent transmission of noise and vibration.

**Figure 1. All-welded 96-ft Motor-yacht, Rhonda III.**

Further, serious doubt has been expressed by some that any large shipyard, with personnel experienced mainly in building large ocean-going vessels, could build pleasure craft of the kind that would compare favorably with fine custom craft built by the foremost American yacht builders.

The building of *Rhonda III* has not only disproved these various contentions, but it has virtually set up new standards. The comforts of modern roomy American living and the sturdiness and dependability of a seagoing vessel have been combined with elegance and the finest workmanship. This was accomplished largely with the use of the same techniques and methods as employed in building some 140 large ships at the Ingalls shipyard in Pascagoula.

The *Rhonda III* was the largest yacht built in America during 1954, and the fourth largest that has been built in this country during the last decade. Her main characteristics are as follows:

| | |
|---|---|
| Length, overall | 95 ft, 10 in. |
| Length on waterline | 90 ft, 6⅝ in. |
| Beam, extreme, molded | 20 ft, 10 in. |
| Draft, half-load extreme | 5 ft, 10 in. |
| Displacement, half-load, molded | 147 tons |
| Speed | 15 mph |
| Fresh water capacity | 2503 gal |
| Fuel oil capacity | 4940 gal |
| Propelling machinery | Twin-screw diesel |
| Total horsepower, both engines | 852 normal shp at 650 rpm (980 shp at 683 rpm, at 15% overload—2 hr rating) |
| Cruising range | 2500 miles |

The vessel has a raised forecastle and transom stern. Provision is made for an owner's party of three couples in separate staterooms with separate baths for owner and guest. Forward, below the main deck, is a large full-width galley, a separate crew's mess, enclosed staterooms for captain and cook and quarters for three hands. Three additional hands can be accommodated for long ocean voyages.

The hull is divided into compartments by five water-tight transverse steel bulkheads, thus affording a high degree of safety in the event of collision. Further, the vessel is equipped with the latest navigation and safety devices. Built by Ingalls for their own account, she is suitable and available for service as a United States Coast Guard harbor or patrol vessel in case of national emergency.

### STRUCTURAL DESIGN

The hull framing of this yacht is quite similar to that of a large ship, Figs. 2 and 3, making her sturdy and dependable for ocean voyages. Most of the hull is constructed of 7.65-lb, low-alloy, high-strength, corrosion-resistant steel. Transverse inverted angle frames, 2½ x 1½ x 3/16 in., are spaced at 16½ and 17½ in. centers, with web frames composed of 6 x 3/16 in. web and 3 x 3/16 in. flat bar flanges, spaced as required. A longitudinal stringer is provided about mid-height between tank top and the main deck. Two keelsons on each side extend aft from the engine girders. Forward, there are keelsons in line with the inboard engine girders, extending to Frame 16.

There are seven strakes of hull plating on either side of the flat keel, Fig. 4. The flat keel and adjacent garboard strakes are of 12.75-lb plating (5/16 in. thick). The B-strakes are 8.925-lb plating (7/32 in. thick). The remainder of the hull plating is 7.65 lb (3/16 in.), and the bulwark is 6.375 lb (5/32 in.).

Structural bulkheads are constructed of three strakes, the upper two of 6.375-lb plating and the lower strake of 7.65-lb plating.

The main deck and forecastle deck are of 7.65-lb plating (3/16 in.) and 5.1 lb (⅛ in.). The plating of the house sides and superstructure bulkheads is in general of 6.375 and 5.1-lb plating. Requirements for spacious quarters with 6-ft. 4 in. minimum head room, for comparatively shallow draft and for elabo-

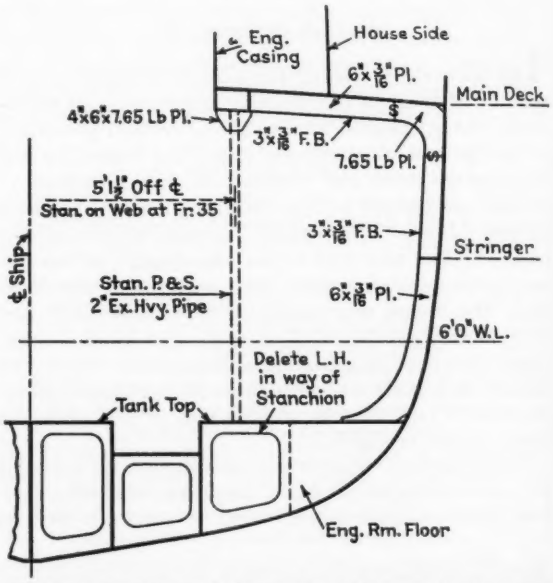


**Figure 2. Typical angle frame, No. 45. Frames 43, 44, 46 and 47 are similar.**

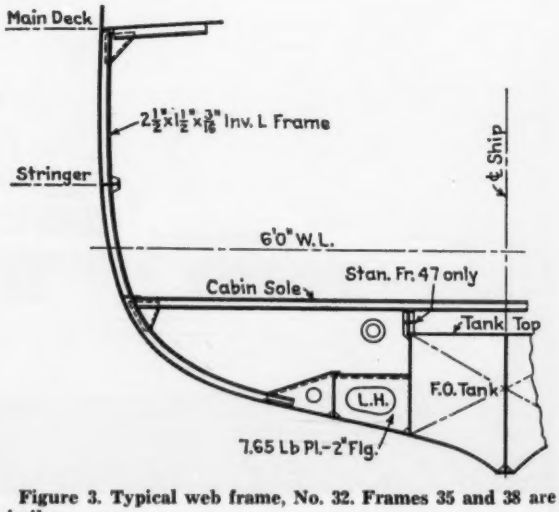


**Figure 3. Typical web frame, No. 32. Frames 35 and 38 are similar.**

rate equipment, all tended to increase the height of the vessel. To minimize weight above the main deck, the boat deck and pilot house top are of plywood laid on steel beams. The cabin sole is of similar construction.

An important objective in the layout of the framing was to provide support and rigidity that would help to reduce hull vibrations and noise at all speeds—hydrodynamic vibrations as well as mechanical vibrations. The inboard engine girders extend the entire length of the vessel and the outboard girders extend aft to the transom, as well as several frames forward of the engine room. Ample athwartship bracing is provided in the engine room and aft, to resist transverse vibrations of the engines. There is sufficient stiffening of the bottom shell to eliminate any excessively large, relatively flat, unsupported panels of plating. Fiber glass insulation of various areas, as well as electrically insulated couplings in the propeller shafting, also contribute to repression of noise.

To minimize warping and distortion due to weld shrinkage, it is very important to specify, and actually use during construction, the minimum amount of welding that is consistent with design requirements and consistent with the construction requirements such as facilitating handling, erection and other operations. As the size of fillet welds is increased beyond such requirements, the tendency toward distortion mounts rapidly.

Load tests, made of sections of plating with lightly welded stiffeners, showed that intermittent fillet welds of quite small size would provide sufficient strength. Calculations showed that the amount of fillet welding required at details, such as bracket connections of deck beams to shell frames, could be reduced to considerably less than the continuous fillet welding that is often shown for such details. The results of these tests and studies were, in a measure, incorporated into the design. However, in doing this, consideration was given to the effect of impact, such as would result from even minor collision, as well as resistance to corrosion in some locations.

Zinc metallizing was applied to all exterior hull surfaces below the waterline and other areas particularly susceptible to corrosion. Areas adjacent to weld locations were masked 1 in. on either side of the joint to prevent contamination during welding. Any zinc spray that was accidentally applied near a joint was removed thoroughly by grinding before the welding was done. Completed welds were cleaned thoroughly before these adjacent areas were finally coated with zinc spray.

### GENERAL CONSTRUCTION FEATURES

Of course, it was not feasible to use prefabrication and subassembly to as great an extent as that employed for big ship construction, which often has involved a good deal of duplication in orders for sister ships. However, it was evident that good use could be made of facilities and methods of fabrication and subassembly that had been developed for building large ships.

Major emphasis was placed on the control of distortion in all construction operations, from the preparation of material, through all operations of fabricating, fitting, welding, assembly and erection. All crafts were made conscious of this objective, and cooperation between them was stressed.

All plate material was ordered to be "leveled" or straightened by mangle rolls at the steel mill, in view of experience which has shown that some distortion in light plating, which has been attributed to welding, actually has been in the plate material as received from the mill.

To control distortion, it is important to avoid excessive fillet weld sizes in construction as well as in design. Experience has shown that electrode characteristics are an important factor in the general tendency among the majority of welders to make oversize fillet welds, particularly in the case of small fillets such as ⅛- or 3/16-in. size.

It has been found that the use of low-hydrogen-type electrodes facilitates the holding down to correct size for small fillets. This may be due to the fact that the technique of using low-hydrogen electrodes involves less manipulation, and therefore, less tendency to build up oversize welds than in the case of conventional electrodes such as the E6010, E6012, E6013 and E6020 types, when the size of fillet welds is quite small. It was largely for this reason that AWS Class E6016 electrodes of 3/32 and ⅛ in. diam were used for all the welding on this vessel.

Fillet welds, in general, were of ⅛-in. size, except in a few connections that required 3/16-in. size. With the exception of locations where strength, corrosion resistance or watertightness required continuous welds, all fillet welds were made intermittent. For example, the fillets for attaching side frames and web frames to the shell plating, and web frames and deck beams to deck plating, were made ⅛-in. size, 1-in. increments at 12-in. centers, with double continuous fillets, 3-in. long, at the ends.

Careful advance planning of schedules is very important—to insure good workmanship and to control distortion as well as to facilitate speed and economy. Apart from the very important role in distortion control that is played by a well-planned welding sequence, it serves to tie other operations together in an orderly fashion, with suitable subassemblies erected in proper sequence. The use of proper welding procedure and technique is also an influential factor in distortion control.

### PREFABRICATION AND SUBASSEMBLIES

One of the first prerequisites for accurate fabrication and subassembly is the provision of fair working floors or slabs, platens and jigs, together with suitable facilities for handling and storing materials and fabricated parts in such a way that they will not be damaged. If welding is done on a part while it is not held fair, the welding will simply lock the part in the distorted shape.

With accurate control of lines and dimensions during prefabrication and subassembly, as well as during erection, proper fit-up was assured. This avoided the

kind of distortion that results from forced fitting. Also it eliminated excessive welding to compensate for inaccurate fitting, and thereby it reduced weld shrinkage distortion to a minimum.

Special attention was given to see that all parts in the vicinity of a welding operation were not only accurately fitted but also properly supported to hold them fair and in correct position during all welding operations. The plating of the welding floors or platens was not less than ⅝ in. thick.

In welding the light-weight bulkhead and deck subassemblies, the plating was first placed on the steel welding floor with the stiffener side down (that is, the side to which stiffeners or deck beams were to be subsequently fitted). The abutting edges of plates were fitted together with spacer-shims, to provide uniform root opening of about 3/32 in., and thus to insure good penetration and provide for uniform shrinkage along the butt joints with little tendency toward angular distortion. Controlled uniform shrinkage also facilitated the prediction of over-all shrinkage of the vessel or subassembly and the resulting loss of dimensions. Sufficient tack welding was done along all butts and seams to maintain proper root spacing and alignment.

Weight boxes on hold-down plates were then placed along the entire length of each butt and seam, on both sides of the joint, as close to the joint as practicable, to hold the deck or bulkhead plating flat and in contact with the welding floor. These hold-down plates were not less than 12.75-lb plate and 2 to 3 ft wide.

The welding of the butts and seams was then done by a wandering or skip welding order of deposition, completing the welding along each butt or seam before proceeding to the next one in the established sequence. This welding was done by first depositing increments of 5-in. length, spaced 18 to 24 in. apart. Next a series of similar increments were deposited adjacent to the first increments, and so on until the spaces were all welded. In way of window openings, the butts and seams were merely tacked and left unwelded. The butts and seams were all worked with a maul and flatter while they were still weighted down.

After all butts and seams in an assembly had been welded from the first side, the plating was turned over and weighted down as before. The butts and seams were then backchipped to sound metal and completed using a similar skip welding order of deposition. The weight boxes and hold-down plates were removed and the weights were replaced directly on the subassembly plating in an arrangement that would clear the stiffener or deck-beam locations.

Next, the stiffeners or deck beams were fitted and tacked, and then welded, usually progressing from the middle of the assembly in both directions.

The sequence of shop operations, as just described, has been found to be suitable both for light plating and also for very heavy plating in which the butt welds are filled to only half the plate thickness or less during the welding from the first side. For intermediate thicknesses the plating may be laid down first with the stiffener side up. Most of the groove depth is then filled when the butts and seams are welded from this side, prior to fitting, tacking and welding the stiffeners or deck beams. The assembly is then turned over for completion of the butts and seams. Since the completing of the butts and seams from this second side involves a comparatively small amount of welding, it can be done in this manner, after the stiffeners or deck beams have been welded in place on the opposite side, without undue restraint from the stiffeners.

The "drum-heading" method of distortion control was tried on two bulkheads. The boundaries of the plating were tack welded to the welding floor prior to the welding of the stiffeners to the plating. After welding, the assembly was permitted to cool before it was released by chipping the boundary tack welds. This drum heading produced no noticeable improvement, probably because the light intermittent stiffener welds did not provide sufficient shrinkage to cause drum heading.

A further refinement was used at some places to minimize the angular distortion at fillet-welded tee joints and to minimize the lines of welts that sometimes occur on the smooth side of the plating, opposite the fillet welds that attach the inverted angle stiffeners, deck beams or frames. In fitting some of these tee joints, both in the shop and during erection of the shell plating, short pieces of 1/64-in. diam soft iron wire spacers were inserted transversely at 18- to 24-in. intervals along the entire length of the tee joint, to breast out the toes of the angles slightly.

The use of such soft iron spacers is particularly helpful when the curvature of shaped plating runs at right angles to the stiffening members, and shrinkage tends to pull the plating flat between the frames or stiffeners, instead of following a fair curved surface.

It is believed that the cost of reasonable refinements to avoid distortion, as used for this vessel, is more than offset by the reduced cost of fairing by flame shrinking and other means after the welding is completed. The importance of accuracy of dimensions of subassemblies and parts cannot be stressed too greatly. Forced fitting is responsible for a good deal of distortion that is especially difficult to correct after a structure has been completed.

### ERECTION

The keel was laid July 26, 1954, on a carefully aligned and leveled grid of steel beams. The main longitudinal beams of this grid were placed far enough outboard that stocks or shores under the bilges could be supported directly over these longitudinal beams, on the outboard ends of the crossbearer beams.

Realizing the importance of accuracy in erection and fitting and their relation to the control of distortion, the frames of the vessel were carefully aligned and continually checked to see that they conformed to the molded lines, in advance of welding operations

on the shell and deck plating. Although care had been taken in fabrication and subassembly work to control shape and dimensions accurately, continual checking was done during erection to be sure that any necessary corrections would be made during the fitting and in advance of the welding—for example, the checking of the alignment of ends of floors and of side frames and deck beams, edges of transverse bulkheads and contour of shaped plates of the shell.

The work of riggers, fitters and welders was coordinated, to conform to the planned erection sequence and welding sequence, so that fitting would not advance too far ahead of the welding at any location. Otherwise, there would have been excessive restraint against weld shrinkage at some points.

Further, when the work is fitted and tacked or rigidly clamped, too far in advance, it can produce the same effect as departing from the welding sequence. Under these circumstances the weld shrinkage can pull parts out of correct alignment or relative position, resulting in permanent distortion that is difficult to remove.

There are some cases of unbalanced welds on a built-up welded member, in which extensive tack welding in advance of production welding will provide more stiffness to resist distortion. However, more often than not, in a large structure, it is desirable to permit weld shrinkage to occur with a reasonable amount of freedom, and not to carry the fitting and tacking much ahead of the welding.

### OBJECTIVE OF THE WELDING SEQUENCE

The term "welding sequence" will be used in the manner that is customary in most shipyards, to denote the progressive order in which the various seams, butts and lengths of fillet welds are made, rather than to denote the order of depositing the various layers of a weld or the various increments along the length of a weld, as when back-stepping or wandering technique is employed.

One of the main objectives of such a welding sequence is to avoid excessive restraint against weld shrinkage that might result in buckling of plating or the structure otherwise being pulled out of proper shape, dimensions or alignment. In extreme cases, excessive restraint, together with other factors, can result in cracking. A further objective is to keep the deposition of welding properly balanced so that inevitable shrinkage forces and their bending moments will not bend or bow a structure or its parts and result in an unfair structure.

In the welding of subassemblies, the general rule followed, as nearly as possible, was to first make all the welds that would tend to shrink the subassembly in one direction, and then follow with the welds that would tend to shrink it in the other direction, welding the butts ahead of the seams, especially when the butts were staggered. Sometimes the subassembly was divided up into two parts and the procedure just described was applied to each of those parts before they were joined together—for example, the case of welding stiffeners or deck beams and intercostal headers to plating in which there were butts and seams.

In the case of the inner-bottom subassemblies the butt welds in the plating were all completed before the cratelike grid or assembly of floors and intercoastals was welded to the plating. Also the latter welding was kept behind the making of the vertical fillet welds that joined the intercostals to the floors. These vertical welds were made by a wandering (skip weld) order of deposition. The welding of the grid to the tank top was started at the center and was carried outward in all directions, keeping this welding close behind the fitting and tacking. This was done because the shrinkage of this last part of the welding tends to cause the plating to contract more than the grid.

In a small subassembly of this kind, its weight would probably not be sufficient to prevent its rising off the welding floor at the middle, if the grid were to be tacked to the plating extensively, in advance of the production welding.

In effect, the sequence for welding these subassemblies was equivalent to dividing the subassembly into two parts and welding each part in advance of joining the two parts together.

### SHELL PLATE ERECTION AND WELDING

The shell plate welding sequence is of special importance because of its influence upon distortion in the shell plating, as well as upon the tendency for the vessel to rise off of the blocks at bow and stern; also its influence upon maintaining the over-all dimensions of the hull. Therefore, this sequence will be described in detail.

The general scheme of the shell plate welding sequence was the conventional one that is used when the shell is erected one plate at a time. It involves starting at the centerline of the bottom shell amidship, and welding simultaneously on port and starboard sides progressing forward and aft and outward or upward, in a "stair-step pattern," Fig. 4.

The framing was welded to each plate after that plate had been welded to the adjacent plates along both edges and along the transverse or vertical butt on the end of the plate nearest midships.

The steps of the shell plate welding sequence are listed consecutively in Table 1. The identification numbers of the welds and the plates as listed refer to the numbers shown in Fig. 4. When the only suffix of a weld number is an F or an A, these letters denote forward and aft, and the welding is done port and starboard at the same time for that weld location. If a P or S is also added to the number, it is because the welding port and starboard is not done at the same time for that weld location, and the letters P and S denote port and starboard.

The shell butts and seams were welded first from the inside. They were then back chipped and completed from the outside. Each butt or seam was completely welded from both inside and outside before welding was started on the succeeding butt or seam.

From this description, the need for close cooperation between the riggers, fitters and welders is quite

evident, as well as the need for cooperation in planning the erection sequence and the welding sequence.

Although the general scheme and pattern of the shell plate welding sequence as described is quite simple, the determining of the exact order of welding the various butts and seams requires a background of experience. Judgment must be exercised in determining the rate of progress forward and aft, with respect to the rate of progress outward or upward. It is the relation of these rates of progression that influence the general vertical profile of the vessel—that is, whether there is a tendency for bow and stern to rise. If the welding progresses too rapidly forward and aft as compared with progression upward on the side shell, the subsequent welding in the upper parts of the side shell will tend to sag the hull.

In one portion of the shell plate welding, in the general vicinity of the deepest part of the stern bar, between frames 51 and 60, a small departure had to be made from a strictly proper and balanced welding sequence. However, this small departure was of little consequence with respect to control of shrinkage and distortion.

At this location, the shape of the lower part of the hull is so narrow and deep that the inside surfaces and the floors or frames would not have been easily accessible for welding after the plating had been fitted in place on both port and starboard sides. It was deemed expedient to depart from the most desirable sequence, in order to facilitate the making of sound welds.

For example, it can be seen from steps 2A-P, 3A-P, 4A-S, 5A and 6A, in this region, that at first, plate A-5 was fitted to the keel plate on the port side only, and the butt was welded between A-5 and A-4 on the port side only, leaving off plate A-5 starboard for access to facilitate the fitting and most of the welding of the floors to A-5 on the port side. The A-5 plate on the starboard side was fitted and welded to the end of the A-4 plate, after most of the welding of the floors had been done to A-5 on the port side. Following this, the floors were fitted to the A-5 starboard plate. Next, the A-5-to-keel seams were welded, port and starboard at the same time. Finally, the remainder of the welding of the floors was done on the A-5 plates, port and starboard, exercising special care because of the poor accessibility for the welding that remained to be done on the floors.

Later on, the same special sequence was applied in fitting and welding the A-6 shell plates and the floors or deep frames in way of these A-6 plates. At this location, access for welding was even poorer, subsequent to the fitting of the A-6 plates on both port and starboard. It was necessary to fit ⅛- x ¾-in. flat backing bars in way of the seams between the half round stern bar and the plates A-6 and B-7, port and starboard. Likewise the lower 15 in. of the butts between A-5 and A-6 plates, port and starboard, were fitted with such backing bars to assure sound welds.

Special care was exercised in making those welds for which it was impossible to improve the accessibility.

All butts and seams in the deck plating were fully welded in advance of the welding of parts of the super structure to the deck. The plating of the main deck and the forecastle deck was erected for the most part as subassemblies, and the erection welding to join the subassemblies together was comparatively simple. All deck butts were welded in advance of welding the deck to the side shell.

### SUPERSTRUCTURE ERECTION AND WELDING

The erection welding of the superstructure was started on the centerline of the vessel near midships at the front of the machinery casing, frame 30½, and it progressed forward and aft and outboard, port and starboard, from that point. Interior bulkheads were erected, fitted and welded together and then welded to the main deck in advance of their being fitted and welded to exterior bulkheads.

The fitting and welding of the exterior bulkheads were started at the middle sections of house sides and this work progressed forward and aft, and simultaneously on the port and starboard sides.

During the progression forward and aft, the tops of the bulkheads were welded to the boat deck beams as they were encountered but the welding together of the framing of the boat deck was kept in advance of the welding of the boat deck to the bulkheads below. As has been mentioned the boat deck and the pilot-house top are of plywood laid on steel beams. The welding of the tops of exterior bulkheads to the longitudinal tie plates of the boat deck was carried along abreast of the welding of these exterior bulkheads to the main deck.

Cutouts for doors and windows in any bulkhead were not made until all the boundaries of that bulkhead had been completely welded. All square corners of cutouts were rounded by drilling holes at the corners in advance of making the cutouts. Where these cutouts were made by oxygen cutting, the cuts were interrupted at intervals not greater than 24 in., leaving short tie-in portions that were left uncut until the plating had cooled to ambient temperature.

The vessel was "launched" on Sept. 30, 1954 when she was picked up by two 50-ton gantry cranes which transported her some 600 ft and set her down in the water.

At the outfitting dock, the plywood boat deck and pilot-house top were installed. Other outfitting operations, such as joiner work, installing of insulation and completion of work on machinery, were performed in much the same manner as for large ship construction. The vessel was completed for delivery on Jan. 19, 1955.

The weight of fabricated steel in the vessel is about 67 tons. Approximately 2500 lb of electrodes were used for the welding, which consisted of some 3600 linear feet of butt welds and about 18,800 linear feet of fillet welds.

More detailed information on some of the features of design and construction that are not particularly related to welding are given in the April 1955 issue of *Marine Engineering*, pp. 50–55, under the title *"Rhonda III*, New High in Yacht Design."

*General Welding Notes*

1. In general, all welding shall progress on the port and starboard sides simultaneously unless specifically noted otherwise.
2. (a) Use the wandering sequence (skip weld) method for all welding, whether intermittent or continuous. (b) Maximum length of weld bead increment deposited in making a continuous weld shall not exceed 5 in. in length. The spacing between consecutive increments shall be approximately 18 in.
3. When welding tee joints, welding shall be kept symmetrical about the stem of the tee in so far as is practicable.
4. The sequence for fitting shall conform closely to that shown for the welding (see Fig. 4).
5. The fitting and any necessary tack welding shall progress not more than a reasonable distance in advance of the welding.
6. Shell plates shall be securely fastened to the floors, frames, etc., by clamps, dogs and wedges, or other devices in such a way that the plates will be free to move with welding shrinkage when welding butts and seams, thus eliminating any condition that would produce distortion.

TABLE I—*Shell Welding Sequence for Yacht RhondaIII*

*Procedure Aft* (see Fig. 4)

*Note:* All steps include work on both port and starboard at same time except as noted otherwise.

1. Weld seam A4 to FK.
   Fit floors to A4.
   Fit A5 to FK port side only at this time, leaving off A5 starboard for access.
2A. Weld butt A5 to A4 port side only.
   Fit floors to A5 port only.
3A. Weld floors 51 through 56 to A5 port side only.
   Fit A5 to FK starboard side.
4A. Weld butt A5 to A4 starboard.
   Fit floors to A5 starboard.
5A. Weld seams A5 to FK port and starboard.
6A. Complete all remaining welding of floors to A5 port and starboard.
7A. Weld seam B4 to A4.
   Fit floors and keelson to B4.
8A. Weld floors to A4.
9A. Weld seam C4 to B4.
   Fit floors to C4.
10A. Weld floors, keelson and BH* to B4.
11A. Weld butt B5 to B4.
12A. Weld seam B5 to A5.
   Fit floors and keelson to B5.
13A. Weld seam D4 to C4.
   Fit floors to D4.
14A. Weld floors and keelson to C4.
   *Note:* Provide ⅛- x ¾-in. flat bar backing, in way of seam A6 and B7 to half round stern bar pipe, from frame 57 to 61, port and starboard. Then fit A6 on port only at this time, leaving off A6 starboard for access for welding. Fit flat bars ⅛ x ¾ x 15 in. on after ends of A5, in way of butts A6 to A5 in way of butts A6 to A5 to extend from flat keel upward 15 in.
15A. Weld butt A6 to A5 port only.
16A. Fit and weld floors to A6 port only.

*BH=Bulkhead


BULWARK
MAIN DECK
TANK TOP
CUT&D KEELSON
IND'D. KEELSON
FOCSLE DECK
BASE LINE
65 63 61 59 57 55 53 51 49 47 45 41 39 37 35 33 31 29 27 25 23 21 19 17 15 13 11 9 7 5 3 1

Figure 4. Shell expansion, showing shell plate welding sequence.

17A. Weld butt A6 to A5 starboard side.
18A. Weld seams A6 to FK and half round stern bar pipe, port and starboard.
19A. Fit and weld floors to A6 starboard side.
20A. Weld seam E4 to D4.
Fit tank top, stringer, frames and BH 52 to E4.
21A. Weld tank top to shell and floors to D4 starting on tank top at Frame 35½ and carrying floor welds clear up to tank top (catching floors as they are reached during welding of tank top).
22A. Weld butt C5 to C4.
23A. Weld seam C5 to B5.
Fit keelson and floors to C5.
24A. Weld keelson and floors to B5.
25A. Weld butt B6-B5.
26A. Weld seam B6 to A6.
Fit keelson and floors to B6.
27A. Weld butt B7 to A6 and B6.
28A. Weld seam B7 to half round stern bar pipe.
29A. Weld seam F4 to E4.
Fit stringer, frames and BH 42 to F4.
30A. Weld stringer, frames and BH 42 to E4.
31A. Weld butt D5 to D4.
32A. Weld seam D5 to C5.
Fit frames to D5.
33A. Weld keelson and frame to C5.
34A. Weld seam G4 to F4.
Fit frames to D5.
35A. Weld seam G4 to F4.
Fit frames, BH and main deck to G4.
36A. Weld butt E5 to E4.
37A. Weld seam E5 to D5.
Fit frames and stringer to E5.
38A. Weld frames to D5.
39A. Weld butt C6-C5.
40A. Weld seam C6 to B6 and B7.
Fit floors, keelson and BH to C6.
41A. Weld floors, stringer and BH 62 to B6 and B7.
42A. Weld butt F5 to F4.
43A. Weld seam F5 to E5.
Fit frames and stringer to F5.
44A. Weld frames and stringer to E5.
45A. Weld butt D6 to D5.
46A. Weld seam D6 to C6.
Fit frames, BH and keelson to D6.
47A. Weld frames, BH and keelson to C6.
48A. Weld butt G5 to G4.
49A. Weld seam G5 to F5.
Fit frames and main deck to G5.
50A. Weld frames and stringer to F5 and to G5.
51A. Weld butt E6 to E5.
52A. Weld seam E6 to D6.
Fit frames, BH and keelson to E6.
53A. Weld frames, BH and keelson to D6.
54A. Weld butt F6 to F5.
55A. Weld seam F6 to E6.
Fit frames BH, tank top, stringer and bracket to F6.
56A. Weld frames and BH to E6.
57A. Weld butt G6 to G5.
58A. Weld seam G6 to F6.
Fit frames BH and main deck to G6.
59A. Weld frames, BH, tank top, stringer and bracket to F6 and then weld frames BH, and main deck to G6.
60A. Weld transom to shell.
*Procedure Forward* (see Fig. 9)
2F. Weld butt A3 to A4.
3F. Weld seam A3 to FK.
Fit floors to A3.
4F. Weld butt A2 to A3.
5F. Weld seam A2 to FK.
Fit floors to A2.
6F. Weld butt B3 to B4.
7F. Weld seam B3 to A3.
Fit floors to B3.
8F. Weld floors to A3.
9F. Weld butt C3 to C4.
10F. Weld seam C3 to B3.
Fit floors to C3.
11F. Weld keelson, floors and BH to B3.
12F. Weld butt B2 to B3.
13F. Weld seam B2 to A2.
Fit floors to B2.
14F. Weld floors and BH to A2.
15F. Weld butt D3 to D4.
16F. Weld seam D3 to C3.
Fit floors to D3.
17F. Weld keelson floors and BH to C3.
18F. Weld butt A1 to A2.
19F. Weld seam A1 to FK.
20F. Fit and weld floors to A1.
21F. Weld butt E3 to E4.
22F. Weld seam E3 to D3.
Fit frames to E3.
23F. Weld tank top to shell and floors and BH to D3, carrying floor welds clear up to the tank top as encountered while welding tank top.
24F. Weld butt C2-C3.
25F. Weld seam C2-B2.
Fit frames and BH to C2.
26F. Weld keelson and floors to B2.
27F. Weld butt F3 to F4.
28F. Weld seams F3 to E3.
Fit stringer, frames and BH to F3.
29F. Weld stringer, frames and BH to E3.
30F. Weld butt B1 to B2.
31F. Weld seam B1 to A1.
32F. Fit and weld frames and BH to B1 and then B1 to stem.
33F. Weld butt G3 to G4.
34F. Weld seam G3 to F3.
Fit main deck, frames and BH to G3.
35F. Weld stringer, frames and BH to F3 and then weld main deck, frames and BH to G3.
36F. Weld butt D2 to D3.
37F. Weld seam D2 to C2.
Fit stringer, frames and BH to D2.
38F. Weld frames and BH to C2.
39F. Weld butt E2 to D3.
40F. Weld seam E2 to D2.
Fit stringer, frames and BH to E2.
41F. Weld stringer, frames and BH to D2.
42F. Weld butt C1 to C2.
43F. Weld seam C1 to B1.
44F. Fit and weld frames and BH to C1 and then C1 to stem.
45F. Weld butt F2 to F3.
46F. Weld seam F2 to E2.
Fit stringer, frames and BH to F2.
47F. Weld stringer, frames and BH to E2.
48F. Weld butt D1 to D2.
49F. Weld seam D1 to C1.
Fit stringer, frames, BH and breast hook to D1.
50F. Weld butt G2 to G3.
51F. Weld seam G2 to F2.
Fit main deck, stringer, frames and BH to G2.
52F. Weld stringer frames and BH to F2, and then weld main deck, frames and BH to G2.
53F. Weld butt E1 to E2.
54F. Weld seam E1 to D1.
Fit frames and BH to E1.
55F. Weld stringer, frames, BH and breast hook to D1, and then D1 to stem.
56F. Weld butt F1 to F2.
57F. Weld seam F1 to E1.
Fit stringer, frames and BH to F1.
58F. Weld frames and BH to E1.
59F. Weld butt G1 to G2.
60F. Weld seam G1 to F1.
Fit frames and BH to G1.
61F. Weld frames, stringer and BH to F1.
62F. Weld butt H1 to Bwk. 1.
63F. Weld seam H1 to G1. Begin welding at mid-length and progress fwd. and aft.
Fit fo'csle deck, frames and BH to H1.
64F. Weld frames and BH to G1, and then weld fo'csle deck, frames and BH to H1.
65F. Weld vertical butt to join stem plate BW-1 to shell plating and weld also to breast hooks and fo'csle deck.
66F. Weld short horizontal seam between bottom of BW-1 and D1.

CHIEF MACHINIST JOSEPH E. SCHIRMER, USN

# "AGENDA FOR TESTING A MARINE BOILER"

**THE AUTHOR**

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THE AGENDA for testing a prototype marine boiler is just as important to the overall picture of economy and efficiency of a vessel, as all other phases placed together. It is obvious that without its boiler, a ship is a useless hulk; therefore, the testing of the prototype boiler must be accurate and complete, producing enough evidence to assure the manufacturer, and of greater importance the consumer, that this boiler will do the job expected of it.

The "prototype" of a boiler is actually the first in a class which is especially designed for a certain class of ship and designed to produce enough steam to run the engineering plant designed for installation in that class of ship.

After the designers arrive at their desires for a marine power plant, one of the first things considered is the boiler. Bids are invited from the various boiler manufacturers for a "prototype" boiler for this particular class of ship. It is to be noted here that the prototype boiler is not always the same boiler that will eventually find itself installed in the ship, for during the tests ( changes and recommendations are usually born, and these upon approval are installed in the first boiler installed in the ship. The prototype boiler is actually the guinea pig for test. However, the majority of changes and recommendations are usually of minor nature and to the average eye, there is very little difference in physical appearance between the prototype boiler and the boiler that is eventually installed.

The testing of the prototype boiler is a laboratory test, to make certain that the boiler meets all of the design requirements. The US Naval Boiler and Turbine Laboratory at Philadelphia is the activity which tests prototype boilers for the US Navy. This sprawling layout is ideally equipped for testing boilers, and has ample shop and laboratory facilities to meet the average test requirements. At some phases of the test, when special data may be required, the Engineering Experiment Station is called in to assist.

The Boiler Laboratory is equipped with huge bays, where the complete boiler is erected and made ready to steam. Steam generated by the prototype boiler is used to run assorted pumps and turbines at the laboratory and is condensed in huge condensers and taken back into the feed system. At the laboratory during such a test, everything needed to be known for the test can be either measured or calculated. Fuel and feedwater can be either weighed or metered; the calorific value of the steam can be measured; amount of steam evaporated can be measured; proper sprayer plates and sprayer plate spray angle can be determined; feed water can be tested for alkalinity, salinity, hardness, oxygen; fuel is tested for fire point, flash point, specific gravity, moisture and sediment content, ash content. Suitable types of automatic combustion controls are available for installation on the boiler. Safety valves, soot blowers, burners and registers, flame failure alarms, high-low water alarms, superheat temperature alarms can readily be tested along with the boiler by use of the laboratory's equipment.

During the testing of the prototype boiler, the boiler manufacturers along with the manufacturers

of equipment which is associated with the boiler work in close harmony and cooperation and rarely miss the target date for completion of a particular test.

Once the prototype boiler has been tested and approved it can be installed in the ship or returned to the boiler manufacturer. Usually it is installed in the ship.

After the boiler is installed, there remain a few tests to be conducted under various service operating conditions at sea. These tests are supervised by the Navy's Board of Inspection and Survey and consist of the following:

a. Full power test of 4 hours duration
b. 120 per cent boiler overload test of 2 hours duration
c. Operation of the soot blowers
d. Lifting safety valves by steam; measuring the popping and reseating pressures and the amount of blowback. Any condition of valve simmering is eliminated. (Normally accomplished after trials)
e. Boiler and casing tightness
f. Burner performance
g. Superheaters and thermal alarms
h. Hi-lo water alarms
i. Flame failure alarms
j. Smoke indicators (trace smoke is permissable except in wartime)
k. Automatic combustion controls if installed.

The primary test object is to determine if the boiler is suitable for use aboard *BLANK* ship, and if it complies with the stipulations of the purchase order.

Secondary test objectives are as follows:

1. Information of value for future designs
2. Required modifications, if any
3. Best operating conditions while raising steam; steaming steadily at various speeds; maneuvering and securing both under manual and automatic control
4. Performance curves for information of operating personnel
5. Circulation characteristics
6. Gas temperatures, before, within and after the superheater.

With clear and concise test agenda, future tests can be handled more easily and more quickly by paralleling certain factors obtained from previous tests and eliminating the needless and the mistakes proven by these previous tests. So in the sense of economy and efficiency, it is quite evident that a proper test agenda is a most important factor in the overall picture.

Let us prepare a simple test agenda for a marine boiler It is to be understood that the calculations are approximate; the points desired are hypothetical and the test runs and sequences are suggestive.

Our test boiler is right-handed; air-encased; natural circulation; single furnace; integral superheaters; extended surface economizer; water cooled side and rear furnace walls; submerged conductive-type desuperheater and is equipped with automatic combustion controls embodying provisions for manual operation of the individual boiler components should there be a failure of the control system.

We start by setting down some hypothetical principal particulars and performance requirements:

a. *Heating Surface-square feet*

| | | |
|---|---|---|
| Generating surface | | 7100 |
| Boiler main bank | 6900 | |
| Rear wall | 75 | |
| Side wall | 125 | |
| Economizer Surface | | 6990 |
| Superheater Surface | | 1200 |
| Total Boiler Heating Surface | | 15290 |
| Radiant Heat Absorbing Surface | | 380 |
| Rear Wall | 85 | |
| Side Wall | 151 | |
| Fireside Row Tubes | 144 | |

b. *Design Pressures*

| | |
|---|---|
| Boiler psig | 650 |
| Economizer psig | 680 |
| Casing-inches of water | |
| Between casings | 150 |
| In furnace | 65 |

c. *Design Particulars*

| | |
|---|---|
| Furnace volume-cubic feet | 900 |
| Furnace depth-feet & inches | 8 foot 4 inches |
| Numbers of burners | 5 |

d. *Anticipated Performance*

| | 20 Knots Cruising | Full Power | 120 percent Full Power |
|---|---|---|---|
| Total Actual Evaporation lbs/hr | 100,000 | 260,000 | 305,000 |
| Superheated Steam-lbs/hr | 98,000 | 255,000 | 299,000 |
| Desuperheated steam-lbs/hr | 1,900 | 4,950 | 5,980 |
| Steam drum pressure-psig | | 625 | 656 |
| Superheater Outlet-psig | 550 | 550 | 550 |
| Superheater drop-psig | | 50 max | |
| Superheater temp. F | 750 | 750 | 800 max |
| Superheater temp. tolerance | plus 25 deg., minus 0 deg. F | | |
| Economizer Inlet temp. F | 240 | 240 | 240 |
| Economizer Outlet temp. F | | | 375 |
| Economizer drop-psi | | 50 | |
| Total Equivalent Evaporation lbs/hr | 125,040 | 325,740 | 400,020 |
| Fuel Rate-lbs/hr | | 19,950 | 24,970 |
| Anticipated Efficiency | | 80.6% | |
| Stack Temperature F | | 500 max | |
| Casing Inlet Air Temperature | | 68 | 68 |
| Total Air Flow-lbs/hr. x $10^3$ | | 340 | 490 |
| Cubic Feet Air/lb Oil | | 230 | 250 |
| Draft Losses—Inches of water | | | |
| Casing | | 4.3 | 9.0 |
| Burner | | 12.4 | 23.2 |
| Boiler & Superheater | | 13.2 | 23.1 |
| Economizer | | 8.2 | 15.1 |
| Total Draft | | 38.1 | 70.4 |
| Firing Rates | | | |
| KB/sq.ft RHAS/hr | | 900 | 1125 |
| KB/sq.ft THS/hr | | 23.65 | 29.67 |
| KB/cu.ft FV/hr | | 393 | 489 |

| Desuperheater performance | |
|---|---|
| Design capacity-lbs/hr | 21,000 |
| Steam pressure drop-psi | 50 |
| Steam pressure outlet-psi | 490 |
| Steam temperature outlet | 400 F |
| Steam temperature inlet | 800 |

*Requirements:*

The installation must be capable of satisfactory operation under steady steaming conditions and maneuvering conditions from a port load up to and including 120 per cent full power. The boiler should operate with a minimum of smoke under all conditions including lighting-off.

Steam from the steam drum shall have a solids concentration not greater than 5 ppm when boiler is steaming at overload with drum water approximately 4 inches above design level, and the boiler having 600 ppm minimum chloride concentration and not less than 1250 ppm total solids concentration.

For the 20 knot cruising condition, the superheater shall be capable of heating 100,000 pounds of steam per hour to 750° F. when the economizer feedwater temperature is 240° F.

The submerged desuperheater in the steam drum shall be capable of furnishing the required steam for auxiliary use.

Aggregate capacity of all safety valves including drum valves, based on the pressure specified below, shall not be less than the evaporative capacity of the boiler at full power steaming (305,000 lbs/hr). Superheater outlet safety valve capacity shall be not less than 25 per cent nor more than 30 per cent of the boiler full power evaporative capacity. The drum pilot valve capacity shall be as small as practicable. Each drum valve and the superheater valve shall have a capacity tolerance of minus 0, plus 6000 lbs/hr; that of the pilot actuator shall be minus 0, plus 3000 lbs/hr; capacities of drum valves shall be based upon 5 per cent accumulation above their own popping pressures; the capacities of the pilot actuator and the pilot actuated superheater valve shall be based upon the popping pressure of the pilot actuator with accumulation. The Safety valve popping pressures shall be as follows:

| Valve | Set Drum Pressure (psig) |
|---|---|
| Pilot | 650 |
| Drum | 665 |
| Drum | 670 |
| Drum | 675 |
| Superheater Outlet | 650 |

The wet weight of one boiler, excluding feedwater regulator, combustion controls and feed valves will be approximately 195,000 lbs.

The automatic combustion control system shall maintain a constant steam pressure in the main steam line with a variation not to exceed 5 per cent during steady steaming conditions. It shall be capable of automatically maintaining nearly smokeless combustion with a minimum of excess air over the steaming range of 5 per cent to 120 per cent of full power capacity. Normal maneuvering range shall not exceed 15 to 1. Manual adjustment to maintain optimum excess air during steady steaming and to provide sufficient air for maneuvering and soot blowing is permitted if burners are to be cut in and out, it is desired that this be accomplished manually.

Feedwater regulation shall be accomplished with a three element regulator.

Total dry weight of boiler shall be determined by weighing component parts during erection. Weights of water required to fill the various portions of the boiler wil be determined and corrected to the temperature corresponding to steam drum working pressure and average economizer conditions at full power; from those weights each of the following will be computed:

a. Capacity in gallons from inlet flange of economizer to check valve at steam drum
b. Capacity as in (a) plus boiler to bottom of visible portion of gage glass.
c. Capacity as in (a) plus boiler to steaming level (centerline of drum)
d. Capacity as in (a) plus boiler to air cocks
e. Capacity as in (d) plus piping and superheater to superheater outlet flange.

Prior to boiler operation, casing strength and leakage tests will be conducted and hydrostatics applied to pressure parts. Casing strength will be tested at 150″ w.g. between casings with the furnace at atmospheric pressure. Combined inner and outer casing leakages will be determined, with furnace at atmospheric pressure, and at air pressures between the casing to at least 70″ w.g. Outer casing leakage will be determined with equal pressures between casing and in furnace to 70″ w.g. maximum.

All pressure parts will be hydrostatically tested to 125 per cent of boiler design pressure, except the desuperheater which shall be tested at 250 psig.

The boiler will be boiled out using one small sized sprayer plate then increasing firing rate and rotating the burners in use. Soot blowers will be set in accordance with manufacturer's instructions and soot blowers will be adjusted for proper blowing arc and maintenance of design head pressure while blowing.

*Test Operating Runs:*

Operating runs will be as follows:

Series I Slow advance to full power and to 120 per cent of full power, determining optimum sprayer plates and moisture carryover.
Series II Evaporative efficiency.
Series III Verification of: capacity of boiler and accessories to operate satisfactorily under all normal or abnormal expected conditions; desuperheater performance.
Series IV Adjustment and calibration of automatic controls, and the determining of satisfactory installation of the controls under all steaming conditions.
Series V Performance characteristics of boiler and automatic controls under simulated casualty conditions.
Series VI End-point tests, determining temperatures and velocities at selected locations in the gas path, such as furnace exit, superheater cavity, leaving superheater and main boiler bank.

Operating Runs will be conducted under the following specific conditions:

Series I Demonstrate operability of boiler and accessories at steaming rates to and including overload; ascertain optimum sprayer plates; firing procedures; boiler and superheater characteristcs; determine whether moisture requirements are met.

Using uncontaminated water at design steaming level (drum centerline) with superheater outlet at 550, desuperheater in operation, steadily increase load until full power is reached or excessive carryover occurs. If 120 per cent rate is attained without moisture carryover when using uncontaminated water, chlorinity and total solids will be increased until concentrations of 600 and 1250 ppm respectively are reached. If 5 ppm solids carryover is not exceeded with water 4″ above water level, under that condition of contamination, moisture requirements will be considered met. Water levels will be varied from 4″ above to 4″ below design height. Should carry over exceed the

5 ppm maximum during either contaminated or uncontaminated runs, steam baffling modifications will have to be made.

Optimum wide range sprayer plates, oil pressures, number and arrangement of burners for steaming rates will be determined. The method of controlling firing rate requires operator control return oil pressure over a range to furnish a variable differential over the sprayer plate firing rate range.

Series II Determine evaporative efficiencies at comparable operating conditions. Sprayer plate data determined during Series I runs will be used for this run.

Series III Minimum firing rates and operating pressures at trace smoke, using burner data from Series I. A run at 120 per cent of overload to verify maximum casing inlet pressure and draft loss when using 250 cu.ft. of air/lb. oil. Maneuvering will be conducted using burner data from Series I. Rates through the entire range will be established. Starting with a cold boiler, steam will be raised as fast as practicable without exceeding the maximum gas temperature before the superheater prior to forming steam or 800 F total steam temperature.

Series IV Determine automatic control system performance while operating under steady steaming conditions and maneuvering; establishing a comparison between overall boiler performance attained under automatic control versus that under manual operation. Calibrate and adjust the controls for optimum air-fuel regulation over the entire firing range from 5 to 120 per cent full power. The optimum operating range (15 to 1) possible without cutting burners in or out will be determined. If burners are to be cut, the best method will be determined.

Series V For information of the operating personnel, procedures for changing from and to local manual, remote manual and automatic control will be determined for normal and emergency operation. In addition, the minimum position for the forced draft blower throttle will be determined. Sufficient runs will be made to determine boiler performance under automatic controls. Maneuver the boiler as rapidly as possible and acceleration rates limitations will be established over the 5 to 120 per cent range. Failure of the air or electrical power supply and that to individual control units will be simulated to evaluate their effects and control performances in protecting the boiler under such conditions.

Series VI Determine boiler end-point and data to obtain heat transfer curve. End point runs will be made to determine maximum steaming rate without excessive solids carryover, without exceeding maximum casing pressures or safe circulation ratios. Operate the boiler slowly above normal overload, examining each unit after each increment.

The boiler will be thoroughly inspected after each series of runs.

In conclusion, it is felt that if the engineer follows the above pattern for boiler testing, he will obtain sufficient and accurate data to properly evaluate the boiler and make his final recommendations with authority and the feeling of a well accomplished job.

# *GAS TURBINES AND POWER FROM THE NUCLEAR REACTOR*

**ACKNOWLEDGEMENT**

*This reprint consists of two articles published in the December, 1955, edition of "The Oil Engine and Gas Turbine." Part I was written by E. N. Shaw, editor of a forthcoming new publication called "Nuclear Engineering." Part II is a staff article based on a paper presented by Escher Wyss, Ltd. and American Turbine Corporation at the International Conference on the Peaceful Uses of Atomic Energy recently held at Geneva.*

THE steadily rising cost of coal and oil, and the increasing difficulty in mining coal present a considerable economic problem to an industrialized society. The United Kingdom is particularly concerned with this situation, as alternative sources of power such as hydro-electric schemes, solar energy cells, etc., are either fully exploited or potentially unattractive. The development of nuclear reactors has changed the situation dramatically, and the U.K. can look forward to a period when the quantity of power will present no difficulties, and cost will be comparable with or cheaper than today.

Due to its high capital cost, the reactor power station will, in this country be used as a base-load supply, although in certain countries such as India, which has still vast untapped sources of hydro-electric power, nuclear power will be of greatest value in supplying small isolated communities with limited quantities. It is improbable that nuclear power will be able to compete for some years in small-scale plants with conventional installations—notably oil engines—except where fuel transport costs form a major proportion of the total outgoings. For transportable military power plants, its independence is a great advantage.

## NUCLEAR FUEL

In Britain the choice of fuel for the next few years will be limited to natural uranium or slightly enriched uranium. Subsequently, highly enriched uranium, plutonium and uranium 233 will be available and may be used pure or mixed with natural uranium and thorium. It is significant that although stocks of enriched uranium must be considerably less than those in the U.S.A. as their plant has been operating since 1943, an experimental fast reactor is already in course of construction at Dounreay. "Fast" implies no moderator, the concentration of fissionable material being high enough for use with fast neutrons.

Moderators for thermal reactors will be either graphite, heavy or light water. Graphite is relatively inexpensive, and can be machined conveniently. Its cross-section is small and it was chosen as the moderator for the first two experimental reactors at Harwell and for the two power reactors being constructed at Calder Hall. It is not as efficient a moderator as water, and therefore tends to make the reactor massive. It is particularly suitable for large medium-temperature reactors. The chief objection to heavy water is its high cost. As has been said, it is an efficient moderator and lends itself to a compact high flux reactor. No other cooling agent is required. E-443 in the course of construction at Harwell has been designed for production of radioisotopes and for materials testing. It is heavy water moderated. Light water, though admittedly cheap, has a significant cross-section for thermal neutrons and is only useful in conjunction with enriched uranium. It suffers from the further disadvantage that the moderating effect may be less significant than its absorption effect, and a reactor using light water may not be "inherently safe." Nevertheless, it is a popular moderator for small research and experimental reactors and may be used for small power reactors.

The cooling and transfer of heat from water-moderated reactors presents few difficulties. The operating temperatures are limited and power will be generated via a heat exchanger and steam turbine. The graphite moderated reactor can be liquid, vapor or gas cooled. As with the moderator, the coolant must have a low cross-section to thermal neutrons, and must not react chemically with fuel elements or constructional materials. Air, carbon dioxide and helium are suitable gases. The first two are inexpensive

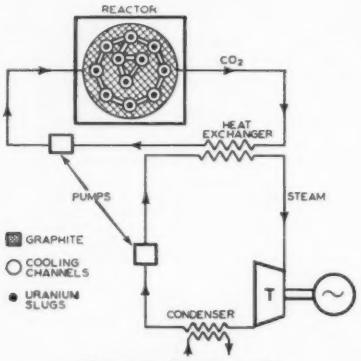


**Figure 1. Steam cycle.**

and readily available. A recycling system is not essential with air, although filters are necessary to arrest radioactive dust and escaping fission products.

SINGLE-FLUID CYCLE

Bepo at Harwell is open cycle and air cooled, while the two reactors at Calder Hall are recycled carbon dioxide cooled. At Harwell heat exchangers have been installed in the effluent gas for central heating purposes only, but at Calder Hall the secondary coolant will drive steam turbines which in turn will drive the alternators. (See Fig. 1.)

It is clear that, as the effluent gas of Bepo is exhausted to the atmosphere, it is not impracticable to insert the turbine directly into the primary coolant stream (Fig. 2). A small contamination of the turbine will occur, but the accumulation of long-lived radioisotopes on the turbine blades should not be serious. Continuous monitoring of the channels circulating gas and of the cooling channels will be made to keep the gas-borne activity to a low level. Traps and filters will further assist in this without causing a serious impedance to the flow. The chief handicap at present is the running of the reactor at a sufficiently high temperature to make a gas turbine system efficient. It is usual to "can" the uranium in aluminum which by its lightness and good conductivity, relative chemical inertness, moderate cross-section and cheapness provides a reasonable compromise of the ideal characteristics. Its ductility is also an advantage in that not only does it remain relatively stable under the intense bombardment it receives, but also will take up limited deformations of the uranium. The behavior of materials under intense irradiation and at high temperatures is one of the more closely guarded secrets. It is safe to say that an operating temperature of 200° C. can be accommodated and that this figure will rise steadily in the next few years. Considerable experimental work is being done on optional canning materials. Reports have been made that an operational temperature of 600° C. should soon be practicable.

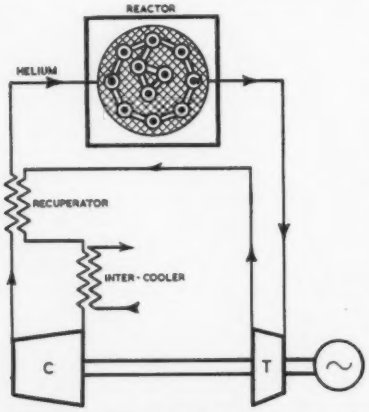


**Figure 2. Cycle with a gas as both coolant and working fluid.**

For fast reactors using stationary fuel elements the problem of heat removal is much more acute. Reactor cores will be small and the concentration of heat generation intense. Liquids will almost inevitably be necessary as cooling agents, and liquid metals such as sodium or sodium-potassium alloys are favored. Heat exchangers are again almost inevitable, although the design of a gas turbine with a metallic gas as both coolant and working fluid with condensation or not cannot be ruled out completely. The choice of the secondary coolant can be fairly wide, although violent chemical affinity between primary and secondary coolant (such as water and sodium) is undesirable. As core temperatures will tend to be high, it is probable that high-efficiency gas turbines will be employed. Either closed or open systems can be used, but to eliminate danger from accidents either to the reactor or, more particularly, to the heat exchanger a closed system will be preferred (Fig. 3).

Designs of homogeneous reactors both thermal and fast are already in existence. In the thermal homogeneous reactor, fuel, moderator and coolant are contained in one solution or slurry. Arguments in favor of a homogeneous reactor are that as uranium rods must be processed periodically to extract the fission products and plutonium, this can be performed continuously with liquid fuel, and heat transfer is highly efficient. The same argument applies to fast reactors where the fuel might be a slurry of a uranium bismuth compound in molten bismuth. The system of such a reactor, shown in Fig. 4, may be similar to that in Fig. 3, except that in between the cold end of the exchanger and the input to the reactor would be installed a separation plant. Admittedly this is not entirely essential as a batch system can still be applied, using an additional primary coolant.

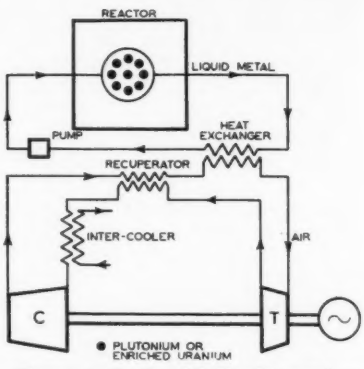


**Figure 3. Cycle with liquid metal as reactor coolant.**

Discussion has been limited to cases where the total heat generation occurs in the reactor itself. There is no reason why coal- or oil-fired cells should not reheat the primary, or preferably secondary, coolant. If corrosion at high temperatures cannot be kept to a low level in the reactor such a system may well provide the simplest solution to utilizing the high efficiency of the gas turbine. Furthermore, with such a system the reactor can be run on a continuous loading, and the reheat adjusted to accommodate variations in output power requirements. Reheat will no doubt be more attractive to countries with greater reserves of coal and oil; but, on the other hand, the addition

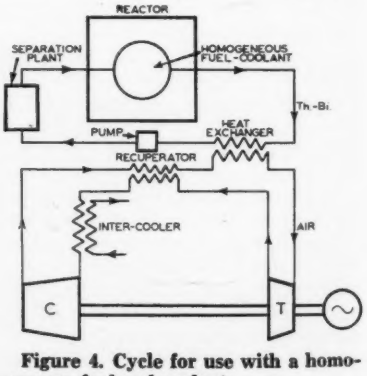


**Figure 4. Cycle for use with a homogeneous fuel and coolant.**

of reactors may prolong the useful life of existing plants.

Looking into the future is far from easy. The first-ever nuclear reactor was not completed until December, 1942, and a bare nine years have elapsed since the Atomic Energy Research Establishment began. The Government White Paper of February of this year has shown that Britain is already committed to a growing nuclear power program; and industry is being encouraged not only to implement the ideas of the United Kingdom Atomic Energy Authority but, in addition, to develop its own designs. The Geneva conference also provided an impetus to plant manufacturers, underlining the international and competitive aspects. The fusion process received considerable notoriety with the first hydrogen bomb, and already there are rumors that the principles of control for a fusion reactor are understood. It may be that fission reactors will still be in their infancy when fusion reactors supersede them. Nevertheless, experience gained in the fission field will be of valuable assistance in controlling and utilizing what is essentially a more violent reaction. Whatever the future trends, it is certain that materials will be developed which will withstand increasingly severe conditions and that operating temperatures will steadily rise. In view of this, it is not unreasonable to expect gas turbines to be in use in about seven years' time.

All present nuclear power stations and, so far as is known, those now under construction, convert heat produced in the fission process into electrical energy through the medium of steam machinery. With maximum temperatures available in present-day reactors, steam turbine plant is undoubtedly the answer because it can use these low temperatures reasonably efficiently. But there is considerable incentive to increase reactor temperatures and when materials and techniques have been improved to make this possible, a case will exist for the use of gas turbine machinery instead of its steam counterpart. This is on account of higher efficiency and easier integration with the nuclear side of the power station. Applying the gas turbine in this field involves certain problems which have no precedent in previous or current technology. Although of considerable interest it is not possible to deal here with them all, but a few of the implications are

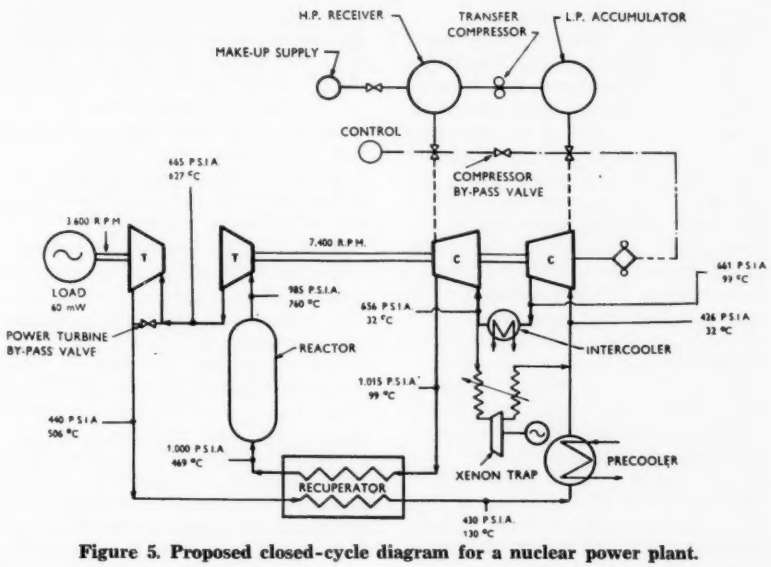


**Figure 5. Proposed closed-cycle diagram for a nuclear power plant.**

presented in connection with a design study for a closed-cycle machine using helium as the working fluid.

### POSSIBLE CYCLES

Various cycles are theoretically possible for using heat available in a reactor and it is by no means clear, as yet, which of these will prove the most acceptable in a practical power station. For the purposes of this article, however, a cycle basically of the type shown in Fig. 5 is dealt with.

Only basic difference in cycle layout between an ordinary combustion gas turbine and one using nuclear fuel is the method in which heat is introduced into the working fluid; one has a combustion chamber, or air heater, the other has a reactor in the circuit.

### OPERATORS' SAFETY

Owing to the danger of radioactivity to personnel and the desirability of not shielding the turbo-machinery, it is necessary to use for the working fluid a gas which has a negligible "neutron capture cross-section" and which will not itself become radioactive even though it is passing through the core of the reactor. For practical installations, this requirement excludes air. An eminently suitable gas is helium because, in addition to satisfying the above requirements, it is inert and therefore problems of chemical attack are absent. It also has good heat-transfer qualities.

Using any gas other than air restricts the choice of cycle to a closed one, but in any case the closed cycle is more attractive than the open cycle because it allows the use of a single circuit in which $T\ max.$ can be more nearly equal to the maximum temperature of the plant.

The closed cycle is also attractive from the standpoint of high efficiency for a given $T\ max.$, as the use of a pressurized, clean, isolated working fluid permits the practical employment of very effective heat exchangers, and also low pressure ratios for optimum efficiency.

Assuming that a closed cycle, working on helium, is chosen, the next important variable about which to make a decision is maximum temperature. It is uncertain at the moment whether maximum cycle temperature will be limited by the gas turbine or by the reactor side of the plan. For the simple cycle under consideration, nothing much can be done in the latter case except await developments in reactor design. On the other hand—perhaps a rather optimistic example—if reactor coolant becomes available at a higher temperature than the turbine can use, then a scheme such as that shown in Fig. 6 is one method of arranging the cycle.

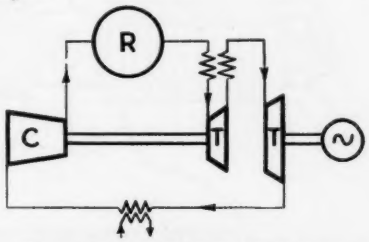


**Figure 6. A method of utilizing reactor coolant which is at a temperature in excess of $T\ max.$**

### HELIUM IMPLICATIONS

Helium has different gas properties to air and this affects the design of the turbo-machinery. Cp, the specific heat at constant pressure, is some five times that of air, resulting in a proportionately lower temperature rise per compressor stage for the same blading velocity diagram and same enthalpy input per stage. This would normally require more stages but for the closed cycle under consideration the temperature ratio would be less than in a comparable air cycle, so that the actual number of stages would be about the same.

Sonic velocity in helium is about three times that in air, hence Mach number restrictions are not present, and blade-tip speeds are limited only by structural considerations. The high heat-transfer coefficient of helium is advantageous in so far as heat exchanger and intercooler performance is concerned giving an increase of around 5% in effectiveness for the same unit using air.

### EFFECT ON MECHANICAL DESIGN

Mechanical design of the plant is also affected in a marked degree when helium is used. Because helium is not ubiquitous like air, sealing arrangements must receive special attention and leakage be kept to a minimum, mainly in view of the cost of replacement. For similar reasons it is necessary to provide a storage system when some of the working fluid is removed from the system during a load change. This is referred to later.

### XENON REMOVAL

Helium is available commercially at a purity of 99.99%, the impurities consisting of argon, carbon dioxide and nitrogen; but none of these is in sufficient quantity to be of any concern. There is, however, the possibility of contamination of the system by gaseous fission products escaping from the reactor fuel elements. Principal volatile radio-active impurity of the fision process is xenon, and removal of the xenon from the working fluid is desirable to reduce the activity of the working fluid to an acceptable level and avoid the necessity of extensive shielding.

Xenon can be removed by solidification in a cold trap. A small percentage of the helium flow (about 1%) is bled from the main compressor intercooler outlet, and cooled in a heat exchanger (see Fig. 5). The xenon will then solidify on the tubes of the heat exchanger and the clean helium will pass through a turbo-expander—incidentally producing a small amount of electricity in the process—after which it will be at a sufficiently low temperature to act as a refrigerant to cool the incoming contaminated helium in the heat exchanger. From this exchanger it then passes to the L.P. compressor inlet. Clogging of the exchanger passages with xenon and its decay products will take place, and eventually the unit will have to be replaced or cleaned, depending on which is found to be economically the best method. In any case this is not a major item as it only deals with 1% of the gas flow and hence is of very small proportions. For the same reason, loss in plant efficiency due to xenon-removal bleed flow is not high.

### CONTROL SYSTEM

As in all closed-cycle plants, load control is by adjustment of the pressure level in the circuit in addition to regulation of heat input. In the case of the helium closed cycle, of course, gas not being circulated must be stored for future use, instead of merely discharging to atmosphere, as with the normal air machine. This is done by means of an accumulator and receiver interconnected by a transfer pump and is shown diagrammatically in Fig. 5. Any leakage losses are made good by additions of helium to the receiver as required.

Because the reactor will have its own temperature control, the only type of control needed on the gas turbine itself is in regard to pressure which is proportional to the load. Hence, if the reactor outlet temperature is constant at most load conditions, thermal efficiency will also remain high over most of the range. This is illustrated in Fig. 8.

In connection with emergency tripping of the plant, the engine governor will shut down the machinery and the control rods will be dropped into the reactor thus reducing the heat input into the system, but means must be provided to circulate the helium through the system for some time after shut down to cool the mass of the reactor.

### DESIGN ASSUMPTION

Gas condition figures given in Fig. 5 have been calculated, using certain design assumptions, the more important of which are shown in Table I:

TABLE I

*Design Conditions and Assumptions*

| | |
|---|---|
| Helium mass flow | 220 lb./sec. |
| Pressure Ratio | 2.4 to 1 |
| Total pressure loss | 7% |
| Minimum cycle temperature | 32°C. |
| *T max.* | 760°C. |
| Heat exchanger effectiveness | 93% |
| Compressor adiabatic efficiency (each) | 88% |
| Turbine adiabatic efficiency (each) | 88.8% |
| Generator efficiency | 97.5% |
| Mechanical efficiency | 97.5% |

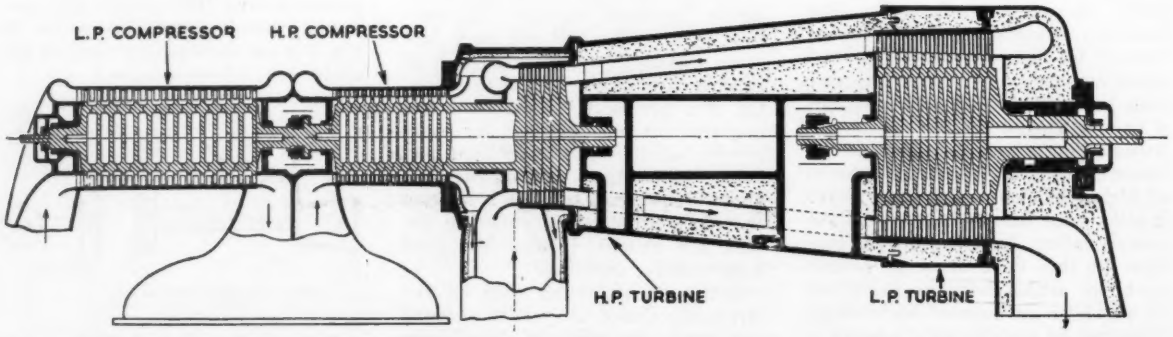


**Figure 7. Section through a proposed turbo-compressor group for use with a gas other than air as the working fluid. Special attention has been given to prevention of leakage.**

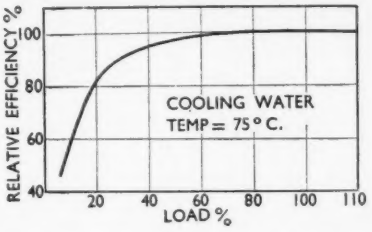


**Figure 8. Typical efficiency curve for a closed-cycle design with load control by pressure level.**

Single intercooling was chosen as two-stage intercooling would result in an increase in cycle efficiency of only 2% at the cost of an increase in pressure ratio of 16%, and some extra complication of the plant.

The authors of the paper give a figure—optimistically—of 760° C. as a reactor coolant outlet temperature and have taken this figure as the *T max.* for the turbine. Cycles with reheat were considered, but according to curves given in the paper little increase in efficiency was evident and in any case a higher pressure ratio was needed, and more complication inevitable, so that the final cycle arrived at was as shown in Fig. 5.

Optimum pressure ratio for this cycle worked out at 2.4 to 1, giving a pressure ratio for each compressor of 1.55 to 1.

Pressure losses have been assessed at 7%, which figure is based on previous practice with closed-cycle plant. Breakdown of this 7% is given below:—

| | Per cent |
|---|---|
| Intercooler | 0.75 |
| H.E. (high-pressure side) | 1.50 |
| Reactor | 1.50 |
| H.E. (low-pressure side) | 2.25 |
| Precooler | 1.00 |

Loss for the reactor is about one-quarter of that which would be experienced in the air heater of a comparable air-cycle machine.

Compressor inlet temperature is based on a cooling water temperature of 75° F.

Heat exchanger effectiveness has been taken at 93% which is considered a reasonable figure, especially in view of the high heat transfer coefficient of helium (the H.E. of the 2,000-kW. Escher Wyss experimental plant had an effectiveness of 94%).

With these assumptions, cycle efficiency works out at 42.4% and efficiency at the generator treminals, 40.4%.

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# *ENGINEERING ABSTRACTS*


| *Abstract Number* | *Abstract Title* |
|---|---|
| 29–56 | Controllable Pitch Propellers in Ship Propulsion |
| 30–56 | 6 Ways to Prevent Indigestion in Residual-Burning Diesels |
| 31–56 | An Ocean-Based Automatic Weather Station |
| 32–56 | Industrial Gas Turbines—Past, Present, and Future |
| 33–56 | Tomorrow's Cutting Tools |
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| 55–56 | Recent Accidents with Large Forgings |
| 56–56 | Jet Engine Enemy No. 1 |
| 57–56 | Radioactive Tracers Speed E P Lube Know How |


29–56 "Controllable Pitch Propellers in Ship Propulsion"—R. F. Desel; Bureau of Ships Journal, V. 4, n. 12, Apr. 1956, pp 2–6. Naval interest in controllable pitch propellers is due to: application of diesel engines to propulsion plants where ship's mission includes towing; use of high-powered multi-engine propulsion plants and development of gas turbines. Characteristics, elements and controls are discussed. Controllable pitch propeller installations include:

| Vessel | No. of Screws | SHP per Shaft | RPM |
|---|---|---|---|
| YTB 500 & 502 | 1 | 1,200 | 180 |
| YTB 501 | 1 | 1,200 | 180 |
| MSO 421 class | 2 | 800 | 265 |
| | | 1,200 | 325 |
| LST 1156 class | 2 | 3,000 | 300 |
| IFS 1 | 2 | 1,600 | 320 |
| PGM 33 class | 2 | 1,200 | 915 |
| AMCU-LCL (L) | 2 | 900 | 650 |
| MSL | 1 | 160 | 1,000 |

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30–56 "6 Ways to Prevent Indigestion in Residual-Burning Diesels"—Gregory Flynn, Jr.; SAE Journal, V. 64, n. 4, Mar. 1956, pp 35–38. Residual fuel can be burned in large slow-speed marine diesel engines with success because combustion is complete, due to slow speed, and operation is at full load during greater portion of time. Locomotive diesels are smaller, operate at higher speeds and have longer idle periods, 30–50 percent, than marine engines. The residual fuel has a higher viscosity and contains more contaminants than the distillate. Methods of reducing troubles en-

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countered with residual fuel burning include: blending residual with distillate; removing water and contaminants by purifiers; heating the fuel before it reaches the injector; starting and idling on distillate and cruising on residual; using improved crankcase oil and draining more frequently; increasing water jacket temperature. Photographs show: head and injector tip fouling after light load operation on residual fuel of 100 SSU at 100° F; head and injector tip relatively free of fouling after light load operation on distillate fuel of 38 SSU at 100° F.

31–56 "An Ocean-Based Automatic Weather Station"—National Bureau of Standards Technical News Bulletin, V. 40, n. 3, Mar. 1956, pp 38–39. This marine weather station, developed by The National Bureau of Standards, automatically reports local weather by radio. It can be anchored in remote locations and left unattended up to six months. The station broadcasts, in code, throughout the day, air temperature, water temperature, barometric pressure, wind speed and direction. The broadcast range is in excess of 800 miles.

32–56 "Industrial Gas-Turbines—Past, Present, and Future"—G. R. Fusner; General Electric Review, V. 69, n. 2, Mar. 1956, pp 49–53. During the past seven years these gas turbines have accumulated a total operating time of more than 1,000,000 hours or 114 machine years. The present operating hours are being increased at about five machine years per month. These operating hours have been obtained in many services including railroad, petroleum, petrochemical, natural gas transmission and electric utilities. Comparative monthly costs of gas turbines, steam and diesel in freight-train service is:

| | Cents per 1000 gross-ton miles | | |
|---|---|---|---|
| Item | Steam | Diesel Electric | Gas-Turbine Electric |
| Repairs | 27.44 | 16.56 | 14.45 |
| Enginehouse expense | 14.89 | 3.66 | 2.24 |
| Fuel | 54.99 | 20.12 | 22.23 |
| Lubricants | 1.47 | 1.40 | 0.47 |
| Other supplies | 5.65 | 0.16 | 0.04 |
| Enginemen | 18.28 | 18.79 | 14.22 |
| Trainmen | 22.42 | 23.34 | 15.54 |
| Total | 145.14 | 84.03 | 69.19 |
| Total for same month (one year earlier) | 130.67 | 85.78 | 87.32 |

Future applications include: marine propulsion; compressed air source for chemical processes; mechanical drive for centrifugal pumps in oil pipelines; electric utility uses in combination with steam plants; drive for boiler feed pumps; locomotive drives; atomic energy.

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33–56 "Tomorrow's Cutting Tools"—American Machinist, V. 100, n. 6, Mar. 12, 1956, pp 154–174. This is a special report on new cutting tools. The report is composed of the following series of articles:

"What We Should Know About Ceramic Tools"—E. J. Tangerman.

"A Roundup on Tomorrow's Tool Materials"—H. K. Siekman, E. W. Goliber, and K. W. Stalker.

"Czechs Cut Cast Iron With Ceramics"—David Scott.

The new materials, ceramics, nitrides, borides, and silicides are presented in detail. Results of laboratory and shop tests are given on these materials as compared with carbides and high speed tool steels.

34–56 "Rare Earth Stainless Steels"—H. O. Bever and B. T. Lanphier; Materials & Methods, V. 43, n, 2, Feb. 1956, pp 96–98. The alloying of misch-metal with stainless steels has provided: new wrought alloys with unusual properties; improved mechanical properties in austenitic stainless steels; better hot working properties; and also enables the producer to conserve nickel. Alloy addition of rare earth metals is made by introducing cast forms of misch-metal to the molten bath of steel. A sulfuric acid resisting steel, carpenter stainless No. 20, showed no evidence of attack after 3740 hours of handling hot sulfuric acid (160° F). Type 316 steel failed in this service in four days. A new valve steel, 21–12N, has been developed with addition of misch-metal to 21–12 steel containing nitrogen. This steel has superior forging properties and is suitable for diesel and gasoline engine exhaust valves. Type 310 stainless has shown a 25 percent improvement in stress rupture properties at 100-hour life level by the addition of four pounds of misch-metal per ton. The misch-metal addition improves forgeability and broadens the forging temperature range of many standard stainless steels.

35–56 "Marine Reduction Gearing"—A. W. Davis; The Engineer, Part I, V. 201, n. 5218, Jan. 27, 1956, pp 120–123; Part II, V. 201, n. 5219, Feb. 3, 1956, pp 156–159; Part III, V. 201, n. 5220, Feb. 10, 1956, pp 200–201. The machining, production and design of marine reduction gears are discussed. British Standard Specifications relating to hobbing equipment and accuracy requirements are mentioned. The production and maintenance of good alignment is emphasized. Methods of selecting loading and tooth form are shown. Couplings and their effects on gear performance are discussed. Photographs, tables, curves are included.

36–56 "Naval Construction in 1955"—Raymond V. B. Blackman; The Engineer, Part I, V. 201, n. 5215, Jan. 6, 1955, pp 25–28; Part II, V. 201, n. 5216, Jan. 13, 1956, pp 68–72; Part III, V. 201, n. 5217, Jan. 20, 1956, pp 94–96; Part IV, V. 201, n. 5218, Jan. 27, 1956, pp 125–127. Construction of naval vessels in a number of countries, including the following, is reviewed: Great Britain, Australia, Canada, Unitted States, Russia, France, Italy, Netherlands, Sweden and Venezuela. British work: was

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highlighted by completion of the large fleet aircraft carrier "Ark Royal"; guided missile ships are under consideration; three cruisers, begun over fourteen years ago, are to be completed; a number of fast frigates are near completion; other work includes submarines, minesweepers, patrol craft and seaward defense boats. Australia is to get new additions of aircraft carrier, "V" class super-destroyers, four new fast anti-submarine frigates and four "Q" class destroyers. Canada has a new carrier, "Bonaventure," near completion and new antisubmarine destroyer escorts. United States construction includes: the world's largest aircraft carrier, "Forrestal"; four sister ships of "Forrestal" under construction or projected; new super-destroyers; new types of ocean escorts; the world's first atomic powered submarine, "Nautilus," and other atomic powered submarines; the world's first guided missile cruiser, "Boston," and a second vessel under construction. Russia has under construction eight more cruisers of the "Sverdlov" class and numerous destroyers, and about eighteen large ocean-going submarines were completed.

37–56 "Product Design by Digital Computers"—Marshall Middleton, Jr., Westinghouse Engineer, V. 16, n. 2, Mar. 1956, pp 39–43. The high speed and great storage capacity of the modern digital computer makes it suitable for complete design of many products. Transformers and motors are currently designed by digital computers. Transformers in the range 750 to 20,000 KVA, with basic impulse levels up to 350 KV, and induction motors in the range 200 to 2,000 hp, at line voltages up to 6,900 volts, have been designed by digital computers. Computers may be used in the future to control production flow of materials in widely separated plants. The detailed scheduling of manufacturing steps, ordering of raw materials, and rescheduling of production due to system stoppage may be done by the computer of the future. The digital computer cannot think. However, it removes burdensome tasks from the design engineer and he is able to spend more time on creative work. The computers are helping to alleviate the engineer shortage.

38–56 "The Engineer's Problem"—Philip R. Marvin; Machine Design, V. 28, n. 5, Mar. 8, 1956, pp 70–74. A discussion of the engineer's progress and problems are presented. The engineer's goals and responsibilities are reviewed. Professional development is essential. It has a primary objective of providing the engineer with rewards including financial and prestigewise. Professional groups like the American Bar Association have stressed the development of a higher caliber practitioner while union leaders are emphasizing organized bargaining power.

39–56 "Small Gas-Cycle Reactor Offers Economic Promise"—Farrington Daniels; Nucleonics, V. 14, n. 3, Mar. 1956, pp 34–44. The helium cooled reactor, with graphite as moderator and fuel container, and the gas turbine, offer attractive possibilities for power generation. The design of a 5-Mw plant is described. This includes: plant layout, reactor, fuel units, control rods, reactor cooling, heat exchanger, closed cycle gas turbine, operation, safety, fuel reprocessing, recommendations, and future developments. Development of a molybdenum or tungsten turbine to operate with helium at 3,000 or 4,000° F should be undertaken.

40–56 "What You Can Do About Metal Fatigue"—Allen G. Gray; Steel, V. 138, n. 3, Jan. 16, 1956, pp 68–72. The need to reduce size and weight of machine parts to save materials and dollars brings metals nearer to limits of safe working stresses. Metal fatigue accounts for about 80 percent of operating failures in machine parts. Fabrication and design are the two areas to watch in reducing fatigue failures. Methods of fighting fatigue failure are presented. A series of preventive measures for avoiding fatigue failures in welded steel parts are given. Photographs of failed parts, testing machines and diagrams are included.

41–56 "Mechanical Seals"—Steve Elonka; Power, V. 100, n. 3, Mar. 1956, pp 109–132. The basic operating principles of mechanical seals are described and illustrated. Mechanical types are divided into balanced and unbalanced, and stationary and rotating seals. Materials, construction, cooling and uses are presented. Seal materials are listed for water, gasoline, oil, acids, salt solution and caustics. Photographs, drawings, tables included.

42–56 "'Auris' Sea-Going Experience over Four Years"—The Oil Engine and Gas Turbine, V. XXIII, n. 272, Feb. 1956, pp 380–382. The Shell tanker "Auris" completed in November 1955 four years of sea operation with a marine gas turbine as a part of her propulsion plant. This gas turbine was an 860 KW unit that replaced one of four Diesel engines in the electric drive. Total running time under load is 17,100 hours with 16,000 hours at sea. The vessel traveled some 160,000 miles. Routine operation and maintenance were simple. At sea, soot blowing of the heat exchanger was done every 24 hours and required 10 minutes. Time spent on maintenance in port was considerably less than on the Diesel and was only a fraction of that needed for a steam plant. Only one oil change was made during the four year period. Compressor washing with fresh water and Teepol removed salt deposits from compressor blades. This vessel is to have an entirely new propulsion plant installed. It will be a 5,500 shp gas turbine with mechanical drive. Photographs and references.

43–56 "A Review of Deck Auxiliaries Supplied to Vessels with A. C. Supply"—A. Sidney Brown; The Institute of Marine Engineers Transactions, V. LXVIII, n. 1, Jan. 1956, pp 1–30. This review describes and discusses some of the operations of the following auxiliaries:

1. Winches: special motor generator set, Ward Leonard controls, "group drive," "Maxspeed" cargo winch, Westinghouse & Reliance Cargo Winches, A. C. commutator motor winches,

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single speed squirrel-cage motor winch with two speed spur gear, three-speed squirrel-cage motor winch with single speed worm gear, four-speed high torque squirrel-cage motor type, dual motor squirrel-cage type, stores winches, hatch cover winches, electro-hydraulic winches, overside hoist.

2. Windlasses: Ward Leonard drive, squirrel-cage motor type, slipring motor type.
3. Capstans: anchor cable, warping.

44–56 "Liner Wear and Porous Chromium"—J. M. A. Van Der Horst; The Motor Ship, V. 36, n. 431, Feb. 1956, pp 494–495. Operating experience with porous chromium and unplated liners in engines operating with diesel and heavy fuels is presented. Some data are offered on 36 vessels. Calculations show that a plated liner can cost two times that of an unplated liner and still offer substantial savings on cylinder wear without regard to the other advantages. Rate of cylinder wear in engines discussed may be increased three times by use of heavy fuel. Tables show engine size, wear rates and operating hours.

45–56 "Silencing the Jet Engine is Now Possible"—John Tyler and George Towle; SAE Journal, V. 64, n. 1, Jan. 1956, pp 67–68. Exhaust silencers are under development to reduce jet engine noise during ground and flight operations. A perforated sheet metal ground silencer has undergone extensive test. Flight silencers are under investigation. These silencers would be of an adjustable type so as to permit optional use by the pilot. In areas where jet noise is not objectionable the flight silencer would not be brought into use by the pilot. It is believed that successful flight silencers can be developed.

46–56 "Creative Engineering: Path to Progress"—SAE Journal, V. 64, n. 3, Feb. 1956, pp 74–79, 82. The creative engineering done in ground vehicles and aircraft is discussed. Vehicle developments include: the Rolligon tires with walking beam suspension that have been used on four-wheel-drive Army vehicles in snow and sand with outstanding success; power steering; and new instruments for studying processes in combustion chambers. Discussions of advancements in the aircraft field include materials and methods of handling them. Bearing lubrication, composition, heat-treatment, hardness and vacuum melting are reviewed. Seals, compressor discs and turbine bucket materials, methods of fabrication and limiting use factors are presented.

47–56 "Pneumatic Ducting Systems"—William M. Cattrell; Aeronautical Engineering Review, V. 15, n. 3, Mar. 1956, pp 68–71. Bleed air from the compressor stages of turbojet or turboprop engines offers a major source of pneumatic power. Pneumatic ducting systems supplied with bleed air offer advantages over other methods in simplicity, reliability, ease of maintenance, safety and weight saving. Ducting for the pneumatic system must be capable of handling temperatures from 500 to 900° F. The materials, such as stainless steel, also have yield strengths at elevated temperatures so gage thickness can be 0.008 to 0.020 in. to reduce weight. These systems carry pressures from 50 to 250 psi and velocities to the speed of sound at sea level. Pneumatic systems supply auxiliary power, engine starting, boundary layer control, anti-icing and dynamic control air.

48–56 "Fuel Control and Burning in Aero-Gas-Turbine Engines"—E. A. Watson; The Chartered Mechanical Engineer, V. 3, n. 2, Feb. 1956, pp 91–127. The problems and developments relating to combustion of fuel in aero-gas-turbine engines are presented. Ignition and control, control systems, injection of fuel, combustion problems, ducting, turbulence, study of air flow by water analogy, fuel entry, mechanical problems in combustion chamber design and other subjects are discussed. Three dimensional charts, curves, drawings and photographs included.

49–56 "Resistance of Materials to Mechanical Corrosion"—Russell W. Heinke; Product Engineering V. XXVII, n. 1, Jan. 1956, pp 194–197. Common mechanical corrosive attacks include: cavitation, stress-corrosion cracking, corrosion fatigue, impingement corrosion, erosion and fretting. Causes of these types, except cavitation, possible remedies and resistance of most common materials are presented. Stress-corrosion cracking is the result of combined electrochemical corrosion and static stress. Corrosion fatigue is the reduction in apparent endurance limit due to the combined action of electrochemical corrosion and a cyclic stress. Impingement corrosion is the degradation of the material associated with turbulent flow of a liquid. Erosion is the destruction of a material by the abrasive action of a liquid or gas. Fretting corrosion is surface damage that occurs when two solid surfaces are in vibrating contact under high unit load—various metals and their reaction to the types of corrosion are presented in tabular form. Photographs and references.

50–56 "Carbon-Dioxide Shielded Consumable-Electrode Arc Welding"—G. R. Rothschild; The Welding Journal, V. 35, n. 1, Jan. 1956, pp 19–29. Investigations have been in progress for several years to develop means for lowering welding costs by use of carbon dioxide for shielding. A successful method has been developed to produce sound welds on mild steels. Close control of variables must be maintained and electrodes must contain sufficient manganese and silicon. The following are discussed: method of supplying carbon dioxide, flow characteristics of the gas, chemical activity, properties of weld metal, operating characteristics, weld contour and applications. In summary the following points are offered:

1. Large amount of splatter is produced.
2. Machine welding gives best results.
3. Manual welding can be performed satisfactorily.
4. Carbon-dioxide-shielded arc welding should be investigated for welding mild steel in high production.

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5. This process is not recommended for any metal other than mild steel.

51–56 "Small Shop Tooling Makes Hollow-Blade Jet Stators"—John P. Wright and Walter F. Hamann; American Machinist, V. 100, n. 3, Jan. 30, 1956, pp 97–104. Hollow stator blades for gas turbines offers attractive weight savings. The formation of hollow blades from sheet metal has presented many difficult problems. The procedures, tooling, contour machining, stretch forming, assembling, pure-copper furnace brazing at 2025° F, airfoil checking, assembly and inspection are described. Photographs and drawings.

52–56 "Designing Aluminum Forgings"—A. E. Favre; Machine Design, V. 28, n. 2, Jan. 26, 1956, pp 76–84. New giant forging presses operated under the Department of Defense Heavy Press Program will make possible new design changes of extreme value to the designer. These presses can apply up to 50,000 tons pressure. The dies can accommodate a working area as large as 10 x 23 ft. Alloy selection affects forgeability. Aluminum forgings are used in preference to other engineered parts because of superior mechanical properties. Forging permits formation of the tough fibrous material to conform to outlines of the part and places the principal loads in most favorable grain direction. Proper design assures maximum properties in a forging at a minimum cost. Alloy 7075 is a superstrength aluminum forging alloy (75,000 psi tensile). Care is essential in design to reduce forging problems and increase die life. Other alloys, each with specific properties and uses include: x7079, 4032, 2218, 2018, 2025 and 6061. Most important recent advance is that of tolernace improvement. With use of these large forges problems of precision forging become magnified. Illustrations, diagrams, tables and references.

53–56 "Crisis: Nuclear Education"—John Kenton; Nucleonics, V. 14, n. 2, Feb. 1956, pp 21, 52–53. The atomic energy industry in the United States is facing its biggest crisis—the training of engineers, scientists and technicians in adequate numbers. AEC estimates 2,000 well-trained engineers and scientists are needed each year for the next three years. Only 500 are being trained at present. By 1975 a total of 40,000 to 50,000 trained people will be needed in the atomic energy field. Surveys show that only about 35,000 engineers will be trained annually in all fields and atomic energy could utilize 15%. However competition for engineers will be such that this 15% will not be available. Russia has a high powered scientific training program in progress that graduated 34% of its people in 1954 while the U. S. graduated only 8%. Russia produced 53,000 engineers and scientists in 1954 while the U. S. had only 23,000. Government, universities and industry are providing additional training opportunities. AEC is readying for Congress a proposed expanded educational program that would require an outlay of $6,000,000 in fiscal '57. It has recommended that: funds for education be increased; tackle teacher shortage problem by paying higher salaries to get more and higher-caliber people; increase length of school year; set up two kinds of high schools, one having higher standards; industrial firms should "at their own expense make available their scientists and engineers for one-year periods to teach in our high schools, colleges and universities"; industry make additional financial contributions to education.

54–56 "How Can We Reduce Costly Reduction-Gear Trouble?"—Part I, R. G. Woder and Part II, O. M. Gordon; Marine Engineering, V. LXI, n. 3, Mar. 1956, pp 42–47. Part I: Sensible breaking in of the propulsion plant will result in less gear troubles. Some of the conditions that result in gear difficulties include:

1. Failure to interpret gear conditions.
2. Lack of quarterly gear and coupling inspection, annual tooth bearing readings under light and loaded conditions, provided by stripe copper method.
3. Disregard of necessity to reduce speed in seaways.
4. Irregular ballasting.
5. Failure to clean oil sprays and check spray pattern.
6. Failure to take annual bridge-gage readings, parallel plane checks.

Part II: Functions of lubricating oil discussed. Causes of gear tooth failures are:

1. Contaminating material.
2. Mechanical condition.
3. Rough surfaces.
4. Metal failure.
5. Lubrication failure.

A new marine oil has been developed and tested on a number of ships whose gears were in trouble. Experience and case histories with this new marine oil on ten vessels is presented. Results show galling, pitting, spalling, wire edging and fatigue were arrested. Photographs, tables included.

55–56 "Recent Accidents with Large Forgings"—E. E. Thum; Metal Progress, V. 69, n. 2, Feb. 1956, pp 49–57. Since 1953 four large rotor forgings failed either on test or in service. The units were: one of the 125,000-kw, 1800 rpm steam turbines at Tanners Creek Station; a generator rotor forging for a 3600 rpm, 147,000 KVA set; a generator rotor forging for a 3600 rpm, 216,000 KVA unit; a low-pressure steam turbine spindle for a 1800 rpm, 165,000 KW unit. Two failures were due to unduly high stress concentrations introduced by design or repair. The other two failures were due to the lack of proper consideration for the evidence of internal defects found by ultrasonic inspection. Photographs, sketches, curves and references.

56–56 "Jet Engine Enemy No. 1"—Approach; V. 1, n. 8, Feb. 1956, pp 36–38. Foreign object damage is considered to be one of the most serious problems. During a recent 3 month period 105 out of a total of 371 engines went to overhaul prema-

*Abstract Number* *Abstract Title*

turely because of foreign object damage. Objects causing damage have been identified as bolts, nuts, screws, washers, tools, stones, sand, foil, sticks and rags. Over 90 percent were blown into air intakes by other aircraft. NACA's study "Ingestion of Foreign Objects into Turbine Engine Vortices" report that vortices formed by suction of jet engines pick up pebbles.

57–56 "Radioactive Tracers Speed E P Lube Know How"—Power, V. 100, n. 1, Jan. 1956, pp 86–87. Behavior of extreme pressure film was presented by V. N. Borsoff and C. D. Wagner at ASLE-ASME joint meeting, Indianapolis, Ind. Oct. 1955. The mechanism of E P lubrication has been described by W. Davey. Radioactive-tracer technique has been used by Borsoff and Wagner to study E P film formation and behavior. Ferris patented the radioactive technique for evaluating wear in 1914. Pinotti conceived the idea of utilizing a nuclear reactor to obtain radioactive parts by nuclear bombardment. This method made the radioactive technique practical for wear studies on piston rings and reduction gears.

# *BOOK REVIEWS AND NOTICES*

## REACTOR SHIELDING DESIGN MANUAL

Edited by Theodore Rockwell, III

Reviewed by M. L. Ireland, Jr.

This manual was released in March, 1956 by the Naval Reactors Branch, Division of Reactor Development of the A. E. C. and is available at $2.10 per copy from the Office of Technical Services, Department of Commerce.

Shielding Design is one of a series of technical manuals sponsored by the Naval Reactors Branch of the A. E. C. Previously issued manuals cover liquid metals, zirconium, beryllium and a bibliography of reactor computer codes. Additional manuals are in preparation for corrosion and wear in water cooled reactors, naval reactor physics design, reactor core design, reactor plant piping, reactor heat transfer and the metal hafnium.

This entire series of manuals is an effective answer to the complaints that declassification procedures are too slow and that release of previously classified documents on a bulk basis provides the specific information seeker with a "needle in a haystack."

The Shielding Manual contains ten chapters which cover the entire range of design procedures including the essential theoretical background, and also valuable information on shielding materials and methods of construction. Ten authors are listed but as the editor indicates in his preface individual authorship was sacrificed to coherence and the result is obviously well worth the required additional effort.

The first chapter presents basic principles including a justification for the neutron removal cross section concept and a brief discussion of build-up factors for the gamma absorption equations. Specific design procedures are detailed in Chapter 3, "shielding the reactor core" and in Chapter 4, "shielding the reactor cooling system."

Permissible radiation levels, biological equivalents and specific applications of tolerances including considerations of access time, power level and local streaming are given in Chapter 2.

Plant layout factors including distance effect, optimization of primary and secondary shielding, and shadow shielding concepts appear in Chapter 5.

Chapter 6 provides detailed information on physical and shielding properties of usable materials, fabrication and assembly details and operational test procedures for measuring radiation levels.

A separate Chapter (7) is required for the special problems related to safe access after shut down. This chapter includes valuable and previously unpublished information on activation of impurities in the coolant system and studies of possible fission product contamination.

Chapter 8 treats the numerous problems of shield penetrations and other irregularities such as defects in a specific and practical manner. The gamma scattering problem at shield boundaries is also thoroughly covered.

The final Chapters, 9 and 10, provide a summary of the reference mathematics (including derivations) for radiation flux geometry and basic data and curves for build-up factors, absorption coefficients, cross sections and radiation damage summaries.

It is hoped that this brief summary conveys some idea of the immense amount of shielding information collected from many sources which are still classified and presented for the first time in a single volume, which is now available to the public.

The fact that an entire series of such manuals covering naval reactor technology is being issued is attributable to the foresight of Rear Admiral H. G. Rickover who has permitted the work to be done by qualified engineers, physicists and mathematicians even at the expense of urgent daily commitments.

## ENGINEERING DRAWING AND GEOMETRY

By Randolph P. Hoelscher and Clifford H. Springer
Published in 1956 by
John Wiley and Sons, Inc., New York, N.Y.
and
Chapman and Hall, Ltd., London
450 pages plus appendix
Price $8.00

Reviewed by Assistant Professor John W. Neil,
Department of Marine Engineering, United States
Naval Academy.

This book, though almost entirely rewritten, has been based upon the successful organization and methods of a previous book by Harvey H. Hordan and Randolph P. Hoelscher. An average teaching experience of more than 30 years each, plus many years of engineering practice by each of the authors come to fruition in this text. It represents a philosophy of training in drawing which is in harmony with the trend in modern engineering education.

Since this text is designed for engineers, thoroughness in the understanding of principles has been emphasized rather than manual skills. It is from the viewpoint of developing an engineer rather than a draftsman that the subject matter has been presented.

The authors are members of the General Engineering Department of the University of Illinois and have had varied and comprehensive engineering experience. In addition, Mr. Hoelscher served as Chairman of the Drawing Division of A.S.E.E., and since 1949, has headed Sectional Committee Y-14 (American Drafting Standards Manual) of the American Standards Association; Mr. Springer has served as Chairman of the Drawing Division of A.S.E.E. and as Chairman of sub-committee No. 4 (Pictorial Drawing) of A.S.A. Y-14.

After a brief introduction to Engineering Drawing, the following chapters develop the accepted fundamentals of Engineering Drawing in the regular sequence.

*Chap. 1* —"Introduction"—A short coverage of the functions of Engineering Drawing and the professional aspects as applied to the varied fields of engineering.

*Chap. 2* —"Lettering"—A brief history of lettering; the mechanics of hand lettering with emphasis on slant lettering; and an introduction of mechanical lettering guides.

*Chap. 3* —"Use and Care of Instruments"—A complete coverage of drawing instruments, including the newer types of drafting machines. A detailed discussion of ruling pens, inking, and special drafting tools.

*Chap. 4* —"Geometrical Constructions"—Basic geometric concepts, angle, ellipse, tangents, arcs, etc., supplemented with detailed illustrations and illustrations for their construction. In addition, there are practical applications of many of the constructions which add meaningfulness to their construction.

*Chap. 5* —"Geometric Projections"—A short introduction to projection, including its history. The summary includes a table of "Types of Projection," which is excellent for reference study.

*Chap. 6* —"Sketching"—The basic concepts of sketching as applicable to the Engineer. The instructions and illustrations are well suited for the presentation of this important phase of Engineering Drawing. The chapter also provides an interesting introduction to the various types of projection covered in later chapters of the text.

*Chap. 7* —"Orthographic Projection"—A brief, concise coverage of Orthographic Projection covering one, two and three view drawings. This phase of the work is concise and condensed, so that it is suitable for an advanced student, but would not suffice for an inexperienced one.

*Chap. 8* —"Sectional Views"—The latest standards of sectioning practice presented in a clear, understandable manner. The illustrations make this chapter excellent for reference purposes.

*Chap. 9* —"Dimensioning"—The difficult field of dimensioning broken down into a systematic step by step procedure that should make it possible for even an inexperienced student to correctly dimension a drawing. The coverage is slanted toward Machine Drawing, and the majority of the illustrations are taken from this field.

*Chap. 10*—"Fasteners"—Types, construction and representation of the various screw threads, and specification of threads on a drawing. A concise discussion of bolts, nuts, and other types of fasteners.

*Chap. 11*—"Shop Terms and Processes"—A follow-up chapter for dimensioning. Considers the processes of the pattern shop and machine shop in some detail. The final portion of the chapter summarizes heat treatment of metals.

*Chap. 12*—"Drawings for Interchangeable Assembly"—A textbook of material on assembly drawing condensed into one chapter. The chapter covers layout, check assemblies, shop assemblies, installation assemblies, cross hatching, standard details, definition of terms, tolerances, surface finishes, and procedures for checking a drawing. The latest American Standards

Association recommendations have been used throughout. This chapter provides an excellent reference source.

*Chap. 13*—"Auxiliary Projections"—A practical approach to auxiliary projection. Mutilated blocks are used for illustrative purposes. The chapter considers one, two, and partial auxiliary views.

*Chap. 14*—"Geometry of Engineering Drawing"—The basic concepts and relationships of points, lines, planes and solids. A concise coverage of the fundamentals of descriptive geometry.

*Chap. 15*—"Intersections and Developments"—A discussion of the general procedures used in solving the intersections of planes, planes and solids, and solids. Practical applications of these procedures in the development of sheet metal forms, including development by triangulation.

*Chap. 16*—"Axonometric Projection"—The theory and methods of construction for isometric, dimetric and trimetric projection.

*Chap. 17*—"Oblique Projection"—A short coverage of Cavalier and Cabinet projection.

*Chap. 18*—"Perspective"—An interesting coverage of the various types of perspective slanted toward the field of display drawing. The chapter includes a study of shading, shadows, and reflection. There are practical applications of each type.

*Chap. 19*—"Charts and Diagrams."

*Chap. 20*—"Map Drawing."

*Chap. 21*—"Architectural Drawing."

*Chap. 22*—"Structural Drawing."

These chapters are suitable for advanced study in these professional fields. The introductory material is clear but concise in nature and would be inadequate for a fundamental course in these fields. The problem solving method is employed in developing these subjects without it being necessary to apply theoretical design work.

*Chap. 23*—"Pipe Drawing"—A short chapter introduced to give the engineer an understanding of the general functions and characteristics of pipe, pipe fittings and piping systems. American Standard recommendations and symbols are used throughout. The suggested type of problem is an interesting application of isometric and oblique projection.

*Chap. 24*—"Machine Drawing."

*Chap. 25*—"Tool Drawing."

*Chap. 26*—"Welding Drawing."

*Chap. 27*—"Reproduction of Drawings."

*Chap. 28*—"Patent Office Drawings."

These chapters are brief, summary type coverage of material needed by the student for reference purposes as he develops his ideas in design drawing.

*Chap. 29*—"Appendix."

A summary of 60 Tables derived from accepted standards as practiced and recommended by industry.

Engineering Drawing and Geometry appears to be an unexcelled text for advanced engineering study, but the condensed nature of the instructional material appears to make the text unsuitable for a fundamental course. The professional approach to the subject matter indicates a thorough knowledge and understanding of the problems by the authors. The text should inspire every student to develop his own initiative, and better prepare himself for the challenges to come in his professional career.

The coverage of subject matter is broad and inclusive, while at the same time being clear and concise. Every topic is vital, and there is no apparent filler material used in this text. The size of the illustrations made possible by the large page size increases the clarity and effectiveness of the illustrations.

The authors have been consistent in their use of the latest recommended standards and the present practices of industry. The practical applications are appropriate and meaningful, and add considerably to the effectiveness of the text. The text does not include sufficient problems for complete course organization, but work books to supplement the text are available, and their use is recommended.

## NAVAL BOILERS

By Robert F. Latham

Published by the United States Naval Institute

On April 1, 1956 the U. S. Naval Institute announced a new edition of *Naval Boilers*. Originally published in 1950, the book has been completely rewritten and brought up to date by Robert F. Latham, Instructor in Marine Engineering at the U. S. Naval Academy.

*Naval Boilers* is used at the Naval Academy as a textbook for the instruction of midshipmen in their first year of study in marine engineering. Consequently, the subject matter is descriptive in nature and covers only the fundamentals of boiler development, design, and operation. It offers engineers and operating personnel a source of descriptive data on the principles associated with steam generating equipment used on naval vessels, past and present.

The text examines the operating characteristics of the marine engineering plant through study of the propulsion steam cycle found in modern warships. The function of the boiler unit within the framework of the propulsion plant is described, including principles of heat transfer, circulation, and properties of steam.

The history and development of steam generating units from the Roman era to the nuclear power plant are traced, with emphasis on marine boilers used in the U. S. Navy. Considerable space is allotted to the basic features of modern boiler design. One chapter is devoted to a description of operational boiler types. The latest trends in naval boiler design are discussed briefly, including forced circulation and nuclear power.

An up-to-date concept of boiler water treatment is presented and the methods presently used in the U. S. Navy are described, including types and effects of contamination and methods to counteract and prevent contamination. A chapter covers the properties, specifications, tests, and handling of fuel oil, the theory and the practical aspects of combustion, methods of combustion control, description of atomizers and burners used in naval boilers, and trends in burner design and combustion control. The final chapter discusses basic naval power plant arrangements and the factors involved in safe, economical boiler operation and maintenance.

While *Naval Boilers* is not intended to serve as an operating manual or a catalog of specific data, it introduces the beginner, through simple, precise terminology and abundant illustrations, to the fundamental features of a steam generating plant and serves as an excellent primer for furthering practical knowledge. It is presented so that the student will derive a basic understanding of the principles upon which marine steam propulsion is founded, and the presentation is designed to arouse his interest in Marine Engineering.

## SHIPS, MACHINERY and MOSSBACKS

by

Vice-Admiral Harold J. Bowen, USN (Ret.)

Published by

Princeton University Press, London, England

Reviewed by Geoffrey Cumberlege

The following book review appeared in the Annual Steam Number, 1955 of the *Marine Engineer and Naval Architect* (Br.)

Admiral Bowen modestly describes this wholly readable book as the autobiography of a naval engineer. It is more than an autobiography: it tells of his conflict with, and eventual triumph over, the "mossbacks," those reactionary play-for-safety men who thought high-pressure steam turned a warship into a species of floating bomb, and who believed, among other things, that quicker-running unconventional diesels would jeopardise the American submarine service. To describe himself as "a naval officer" does the author less than justice, as all who know something of the development of the engineering side of the United States Navy in the past two decades are aware. Such criticisms are niggling, however, and the book itself puts the mossbanks, the struggles and "the naval officer" in correct perspective. It is a capital piece of vigorous writing, although the technical reader might justifiably wish that the admiral had written more "shop" into it.

Not the least interesting part of the book is the first section: Education, Ashore and Afloat. This tells us much about the American Naval Academy, the old Engineers Corps of last century, the period in the States of "every naval officer his own engineer," the emergence (in 1940) of the Bureau of Ships, and other developments relating to training of naval engineers.

The author's early sea-going experiences are in this section, and they deserve a capital "E." He was posted to the coal-burning reciprocating-engined *Tennessee* (built by Cramp in 1906) on the eve of war in 1914. It was said in American naval circles at that time—and elsewhere, too, for that matter—that the quickest way to learn engineering was to get ordered to a run-down ship as chief engineer. "On that basis I was doing all right," says Admiral Bowen with transatlantic dryness. The narrative amply confirms this but we have no space to tell of his compounding willy-nilly of one of the vessel's triples when crossing to England after war had been declared, or of other incidents. One of these is, however, too good to leave for the readers of the book to enjoy exclusively. The ship had Babcock water-tube boilers and when in the Mediterranean early in the war appreciable salt was detected in the feed water by the usual routine tests. The leak could not be located. Testing in such an old, cramped ship was carried out (with the usual equipment) in a boiler uptake, so difficult was it to find space for such work. Sometimes the salt appeared to come from one boiler, sometimes from another; then it was the feed tank—but *never* could the point of leakage be located. In desperation the author decided to watch the man "who couldn't make a mistake testing water." Patiently they sat in the hot and humid atmosphere of the uptake . . . calibrating . . . and testing. Sweat stood on the fireman-tester's forehead—*and a bead dropped into the sample of water being tested.* The phantom leak had been plugged.

The section on high-pressure, high-temperature steam appears rather early, bearing in mind that this is a compartively recent development. It is the best part of the book to marine engineers although the section on diesel engines which follows it is also cogent stuff, if on the short side for technical readers. Admiral Bowen tells an interesting factual story about the coming and rapid development of high-pressure, high-temperature steam in the U.S. Navy; and it is beyond dispute that the men of vision who were responsible—and he was one of the

foremost—are deserving of great credit. They lifted American naval engineering practice after 1933 right into the van, and no well-informed marine engineer can have any reservation about his admiration for it today. We cannot, however, let the forthright admiral's statement that "the U.S. Navy and not the Royal Navy pioneered in this great advance in naval engineering" pass without reminding him that the British Thornycroft-built destroyer *Acheron* had high-pressure, high-temperature machinery in 1928–30. We saw her launched in 1928 but she did not complete her trials until 1931. As an experiment in the new technique she was a success, returning a full load specific consumption of 0.60 lb. per s.h.p. per hour compared with 0.81 lb. for the other ("normal" steam conditions) vessels of her class. There is no gainsaying that the *Acheron* experiment was handled rather badly. She was made an ordinary operational vessel and so had to take her chance in the engineering sense, with the result that she had a good deal of trouble in her too short life—she was mined in 1940. Regrettably, her Parsons-designed-and-built machinery never had adequate shore testing, bearing in mind the important technical innovation which her installation represented. Worse than this, no proper record was kept of her troubles and their rectification; and the costly and painful lesson which she should have represented to the cause of naval engineering was largely lost with her. Nevertheless she was the first and her performance demonstrated that high-pressure, high-temperature turbines were an important naval advance—and one to the credit of British enterprise, whatever Admiral Bowen has written.

The book has some interesting things to say about the vital policy change made in the U.S. Navy in 1933. Prior to that date American naval engineering practice had been conservative in the extreme, with the principal warship builders tied to "Parsons Ltd." for turbine designs under licence agreement. Most of the American warships built between 1918 and 1933 used saturated steam, with (according to Admiral Bowen) the designs of main turbines, gearing, boilers and feed systems unchanged from those used in the first war. One class of destroyer used steam superheated to 650 deg. F. but apart from this the inference is that "Parsons Ltd." kept the technical brake on and nobody in a position of influence seemed to take this amiss. The old ship-and-engine-builder was gone around 1933, the author tells us, for they could no longer compete with the specialist designers and builders of turbines, gears and boilers. It is interesting to contrast this with today's practice in Britain, where we successfully use both types of firm. Alongside the old-established units of the industry (with Pametrada's excellent facilities in support these days) we have such turbine specialists as English Electric and Metrovick making important contributions to naval steam turbine progress. On the gearing, boiler and feed system sides we are equally strongly served.

The admiral describes most interestingly how tradition was ruthlessly put aside by Admiral Robinson, himself and those who supported them in the urgent matter of getting naval engineering on to a modern basis in a country where for years power station steam practice had been so admirable. In discussing the change of policy which was effected, Admiral Bowen says some very straight things about the Parsons link and the "inbred conservatism of British engineering." Whether or not the author intended it, the impression is left that the Parsons Marine Steam Turbine Company controlled the machinery design policy of the U.S. Navy from England prior to 1933. This policy resulted, we are told, in the "British Admiralty having made available to it the power, speed, and the designs of turbines being installed in American naval vessels," for what that was worth; and the author seems to think that this "siphoning of U.S. naval turbine designs," as he calls it a few lines further on, was a bad thing for the States which the change of policy stopped. Surely, if the designs were out of date, and British-inspired at that, there was little likelihood of the British Admiralty gleaning anything from them?—always assuming, of course, that the Parsons firm, with more patriotism than business ethics, "tipped off" Whitehall. Frankly, we do not believe that this form of one-way "exchange" happened. (Maybe this sort of thing was in mind when the American authorities—charmingly but firmly—declined to let this journal even look inside the machinery spaces of the *United States* when we visited her by invitation!)

When the United States got down to the matter of modernizing her naval engineering she made a real job of it. The famous consulting firm of Gibbs & Cox were called in on the strength of their experience in the design of large liners and their machinery. The latter made use of temperatures approaching 750 deg. F. at that time, much higher turbine speeds were used than the U.S. Navy employed, double-reduction gears were the order, and economizers figured in them. In short, the specifications were in line with the progressive ideas of "the Bowen camp." The famous *Mahan* class of destroyers resulted from this cooperation. No fewer than 26 ships of this class were built and they vindicated the bold change in design policy although their machinery spaces were rather congested. In addition to having high-speed main turbines and double-reduction gears, these destroyers had directly-coupled (i.e. no clutch) cruising turbines. The steam conditions were: 400 lb. per sq. in. and 700 deg. F., although 850 deg. F. had been planned originally. A de-aerating feed system was used for the first time in the U.S. Navy.

The admiral passes on to the machinery of the equally well-known American destroyer *Somers* (600 lb., 850 deg. F.), a large vessel of 51,525 trial s.h.p. which soon followed. Her acceptance trials were in late 1937, and bearing in mind the general practice in the engineering department at Washington a few years earlier the forward step she represented was considerable. She had air-encased boilers with an open stokehold, and controlled superheat and the use of economizers were features.

The scene moves inevitably, in view of the urgent need for rearmament, to larger vessels of war and the machinery for them. As with destroyers, the "Big Three" (Bethlehem, Newport News and New York Shipbuilding) were not at that time in favor of the newer machinery with advanced steam conditions, higher turbine speeds, double-reduction gears and the rest. The book tells interestingly of the opposition to the use of modern machinery and quotes from official memoranda which passed between the author and the General Board of the Navy. The author appears to have had an exceptionally tough job in trying to convince the powers that be that outmoded machinery should not be ordered for the battleships so urgently needed. Such phrases as "gambling with national defense . . . by installing experimental and unproven engine designs" were thrown at the author, at that time Engineer-in-Chief of the Navy, and more than one official body attempted to arrogate to

itself duties and functions in the engineering field which were fundamentally Admiral Bowen's. He also mentions that the British E.-in-C. was often quoted against his policy. Such phrases are mentioned as "Let the Americans and Germans do it, and if it succeeds we will copy them." In referring to the progress already made and the advance to larger installations contemplated, our own E.-in-C. is said to have commented that the U.S. Navy had been "sold down the river by the same big electric manufacturing companies who put over electric drive" on the American Navy in an earlier epoch.

The acrimonious business occupies a considerable amount of space—and well-used space, we think—but it ends rather unsatisfactorily. We know that the views of the admiral and his supporters eventually won the day but this episode of the battleship machinery ends with the Board's peroration saying in effect that they would have none of it. There follows a single sentence, with no date reference to give it weight, that high-temperture, high-pressure machinery was adopted for the *Atlanta* class of American light cruiser, this being the first time it had been used in the States for such vessels. Such machinery, the admiral rightly points out, represented the background of American naval machinery practice during the last war and made possible their fleet's long-range operations in the Pacific. He also instances the inferior cruising range of the less economical units of the British fleet during the war, quoting Captain Russell Grenfell's book, *The Bismarck Episode*, in support. Telling though this is, and of value through the comparison of fuel consumption and cruising radius of certain British and American vessels also is, the narrative suffers somewhat from a tailing off after the heat had been generated and the memoranda flashed a few years before war broke out.

So far as steam machinery is concerned, the rest of the book is of moderate interest apart from the appendices. These are ten in number and they cover some 22 pages. One of them deals with electric drive in warships, a piece of rather old American naval engineering history which is fairly familiar to an older generation of marine engineers but which will no doubt intrigue the younger ones. It is worth recalling that the famous large battle cruisers *Lexington* and *Saratoga*, which eventually appeared as "super" aircraft carriers, had turbo-electric machinery capable of producing 210,000 s.h.p. on trial on four screws. They appeared a good few years prior to the last war.

Another appendix is a press release of 1943 which eulogizes the accomplishments of the Bureau of Engineering, with particular reference to high-pressure, high-temperature steam turbines. Bearing in mind the tough fight of Admiral Bowen to get this very principle accepted in the American Navy, this document of a few years later is not without its piquancy; the pertinacious admiral must have studied it with mixed feelings. It ends by reminding us that in 1939 the U.S. destroyer *Dahlgren* was re-engined and re-boilered with an installation designed for 1,300 lb. per sq. in. and 925 deg. F. That was something to be proud of six years after the light was seen—and sixteen years before this review was written. Since the war, of course, the remarkable *Timmerman* advanced experiment—a destroyer installation of 100,000 s.h.p. with a final steam temperature of 1,050 deg. F. and a pressure of 2,000 lb. per sq. in. on the port set of machinery—has been made and is now being thoroughly tested at sea.

The general reader as opposed to the naval engineer with fuller knowledge may form the opinion from this outspoken book that American naval engineering has left British practice far behind once it shook off the mossbacks. Admiral Bowen has, of course, been "on the outside" for more than ten years, and much has happened. While Britan has not been able to afford the wonderful luxury of a *Timmerman* experiment her naval engineering specialists have not been idle. Some real advances have also been made here since the war, although we have not gone to the very advanced steam conditions of the *Timmerman*; neither have the Americans, for that matter, so far as everyday naval turbine machinery is concerned. We may be able to say more in this connection before long. Meanwhile, let us thank Admiral Bowen for a book which must have done a great deal of good even if it has reawakened some past controversies.

## GAS TURBINES AND JET PROPULSION

By G. Geoffrey Smith
Published in 1955 by
Philosophical Library, Incorporated
15 East 40th Street, New York, N.Y.
Price $15.00  404 pages
Reviewed by W. H. Cullin, CDR, USN

"Gas Turbines and Jet Propulsion" is a meaty book that covers this field in a comprehensive manner utilizing a descriptive style. Mathematics are non-existent in the text. However, an extensive use of curves, tables and schematics serve the author well in conveying a detailed coverage of the how, why, and wherefore of the gas turbine engine and its uses.

As one would expect, the material presented utilizes English and European gas turbines extensively. However, the American contribution is adequately covered in the chapter "American Gas Turbines."

The author first explains the principles and history of jet propulsion, and then goes on to deal with its main technical aspects, including design and per-

formance, components, fuels and fuel systems, metallurgical problems, research, testing and maintenance. The various types of British, American, Canadian and European aircraft gas turbines available or under development are then surveyed, and later chapters examine special applications, such as rockets and helicopters. The final chapters deal more briefly with the use of gas turbines for cars, trucks, power stations, locomotives, marine and industrial purposes.

In Chapter One the author discusses and explains propulsion by jet reaction and makes rather profound statements after stating that the remarkable and well established achievements of the orthodox propeller-reciprocating engine combination have tended to obscure these two facts:

(1) Self-propelled bodies in a fluid medium, aircraft in air and ships in water, progress by reaction to the displacement of a mass of the medium rearwardly. Basically, therefore, all aircraft are jet-propelled.

(2) Despite intensive development, the reciprocating engine with intermittent power impulses is fundamentally a retrogression from rotary units with continuous production of power, such as the early wind and water wheels.

The author states the following, concerning the operation of a rocket, in the same chapter on propulsion by jet reaction:

A rocket, however, is a true reaction unit and a brief examination of its functions serves to make clear the reaction principle on which all the thermal jet plants operate. If a hydrocarbon fuel and oxygen are held in a closed vessel and ignited, the latent heat of the fuel is released, and there is a rapid expansion of the resulting gases. Owing to the fixed volume of the vessel, there will be a rise in pressure which will be uniformly distributed in every direction. As the forces are balanced there will be no tendency for the vessel to move.

Next consider a similar vessel which, instead of being sealed, has at one end an opening or nozzle. On ignition, and combustion of the fuel, the expanding gases will rush out of the nozzle at a high velocity. The internal pressure at the nozzle end of the vessel is thus relieved, leaving an unbalanced pressure at the other end which tends to propel the vessel in the opposite direction to the issuing jet. Obviously it is dependent solely upon internal conditions, and there is no suggestion whatever of the jet "pushing against" surrounding external air. In fact it would function most efficiently in a complete vacuum.

It is considered that the foregoing description of the operation of a rocket engine is misleading, in that the thrust of a rocket is made up of two parts: (1) The differential pressure forces acting as described, plus, (2) The reaction force as a result of the acceleration of the rocket gases out the nozzle as described by the equation $F = \frac{w_p}{g} V_j$ where,

$F$ = force
$w_p$ = weight rate of flow of propellant consumption
$V_j$ = exit velocity or jet velocity relative to nozzle

The statement by the author, that a rocket operates most efficiently in a vacuum, is correct and stems from consideration of the following expression for the *complete* rocket thrust:

$$T = \frac{w_p V_j}{g} + A_j (P_j - P_o)$$

where,
$A_j$ = area of exit or nozzle throat
$P_j$ = exit static pressure
$P_o$ = ambient pressure

It can be seen from the above thrust relationship that with ambient pressure $P_o$ equal to zero, in a theoretical vacuum, with all other variables constant, the thrust would be at a maximum.

In this chapter, entitled "Propulsion by Jet Reaction," the author also states:

A rotary power unit such as a gas turbine has its own peculiar problems but does not suffer the limitations of the reciprocating unit. Its chief merit is a relative simplicity in design, development, and production which arises particularly owing to each component being called upon to perform only one function continuously. Within a considerable range it can be scaled up or down in size and output.

However, in chapter 16, "Turbines for Road Vehicles," the author states:

A turbine of a size suitable for a road vehicle is likely to be more difficult to construct and to be less efficient in operation than a high powered unit for aircraft. The reasons are both mechanical and thermodynamic. It is possible to scale down the dimensions of the components of a 2,500 hp. aircraft turbine but not practical to scale down the limits of tolerance on size, shape, weight and surface finish.

It would appear that the author is not entirely consistent.

Chapter III, "Thrust and Performance," is done in an excellent, readable manner and covers thrust, propulsive efficiency, attitude effects, operating temperatures, component efficiencies and complex gas turbine cycles. Chapter IV deals with the pros and cons of jets vs. propellers including turbo props and ducted fans.

The chapters on gas turbine components, combustion and fuels, fuel systems, metallurgical problems, research, testing and maintenance are covered in a most thorough manner. In fact the chapter on fuel systems is almost too detailed and it is possible to become bogged down and bored except possibly for the student interested in minute design detail. However, a fine description of the Dowty Spill burner, a most unique and simple unit in theory and operation, is contained in this chapter.

The description of the 'torch' ignition system for gas turbine engines is of interest. However, some of the components described are not identified and/or named as typical (e.g., starting routine, air/fuel ratio control unit, etc.). Some confusion exists in the use of terms, for example burner and vaporizer, as meaning one and the same in British content and as the American term, fuel or burner nozzle.

The author mentions a fuel that has a special connotation to this reviewer,—"Hydrogenated cresote," as being one that the Armstrong Siddeley Vaporizer could utilize. Just what characteristics this fuel has is unknown at this moment to this reviewer.

A very interesting and unique method of delivering fuel is described as the French gas turbine "Turbomecas Centrifugal Thrower":

A gear-type feed pump delivers fuel at a pressure of approximately 45 lb/in$^2$ to the forward end of the hollow mainshaft. The fuel passes along the shaft and is flung through radial holes in a thrower disk into the primary combustion zone of the annular combustion chamber. At the high speed of rotation the fuel is raised to about 2,000 lb/in$^2$ pressure, given a velocity sufficient to ensure adequate penetration, and thoroughly atomized. By this method a high pressure fuel pump is not required and the need for a large number of calibrated jets is avoided.

The chapter on British and Canadian gas turbines will open many a reader's eyes. The list of the high-thrust turbo jets and turbo props is impressive. The BE-25 British turbo prop, made by the Bristol Company, has been designed with a very interesting philosophical principle incorporated (i.e., a constant power to a high critical attitude). It is a constant power turbo prop of about 4,000 shp or 5750 ehp at sea level, which is obtained by restricting the fuel flow. Not only does this provide all the power required by most of the immediate BE-25 applications, the author states, and without requiring the development of very large and critical gear boxes and propellers, as needed on larger engines, but it also makes available full take-off power anywhere in the world, regardless of airfield height, humidity and temperature. Normally the BE-25 can develop its full rated power up to about 20,000 ft. by merely opening the throttle.

The only point that mars the treatment of the chapter on British and Canadian gas turbines as well as that on European gas turbines is the time element in the historic treatment of the engines. It is by company engine design development, in types and sizes rather than areas, so that the reader is not always aware of which gas turbine is contemporary and which is one of the pioneers. If one has a lack of familiarity with British engine families it makes for rough going. It seems very poor organization to flit back and forth timewise and gives an impression of a hodge-podge of engines and no continuity in development. However, the descriptive detail of each engine is excellent and includes detail of assembly, material and relevant operating statistics (i.e., temperatures, sfc, ehp, pressures, etc.).

In the chapter on ram jets, pulse jets and rockets, in addition to an excellent handling of the history of these engines, is an eye opening account of the "Escopette pulse jet," a valveless pulse jet that had been developed by the S.N.E.C.M.A. organization in France. In multiple installations of 4 and 6 units they have been used to power the Emouchet sail plane and were first flown publicly at the display in conjunction with the 1951 Paris show.

This chapter is quite comprehensive as can be deduced from the fact that a Loon pulse jet missile being rocket launched from a USN submarine is pictured as well as a pulse jet propelled target drone, the KD2G-2.

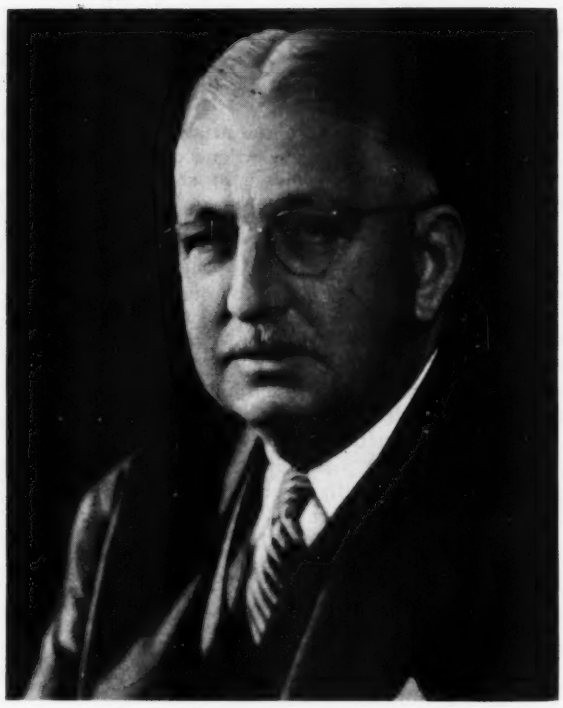
The chapter "Rotating Wing Propulsion" is a most clear, lucid and interesting coverage of helicopters, both past and present, as well as the Foche-Wulf ram-jet-propelled rotating-wing fighter project. Among the helicopters mentioned are the Margaudt M-14 pulse-jet helicopter, McDonnell XH-20 ramjet helicopter, Kaman K-225 three seater with Boeing turbine and mechanical drive, the Hughes XH-17 cargo carrying, jet propelled rotor helicopter and the S.O. 1310 Farfardet convertiplane. The descriptions of these various craft and engine combinations are most explicit, including pertinent flight and operating data.

The author discusses the 'Rover' gas turbine for automobiles, German schemes, Chrysler unit, the Boeing gas turbine unit and the cars or trucks in which they were utilized, in the chapter "Gas Turbines for Road Vehicles."

The final chapter on ships, stationary units and locomotive applications for gas turbine units, is most extensive and complete. The fact that the first gas turbine was available in a hardware stage only approximately 20 years ago makes this review of its rate of progress and accomplishments on the state of the art most impressive and timely.

This book has textbook coverage of the field. The profuse illustrations, schematics, curves and tables of information, enhance the attention to detail and the pains that the author has taken to attain his objective,—a complete, microscopic excursion into the field. The technical narrative style and the descriptive approach make the book extremely readable, except for the treatment of the fuel systems. However, it should be noted that the reader must have a reasonable command of general aeronautical and gas turbine engine terms to utilize this book to the fullest extent.

# O. POMEROY ROBINSON, JR.



**O. Pomeroy Robinson, Jr., pioneer submarine builder and a senior vice president of General Dynamics Corporation, died in New London, Conn., on Monday, Feb. 27, after a brief illness. Robinson was a director of General Dynamics and of its Canadian subsidiary, Canadair Limited in Montreal. He was 64.**

**His death occurred less than 24 hours after he had been stricken with a cerebral hemorrhage at his Waterford, Conn., residence.**

**Mr. Robinson was active for 40 years in submarine construction and for the past nine years also was active in the aircraft field.**

**He joined the Electric Boat Company, predecessor to General Dynamics, as a chaser in 1915 following schooling at Amherst College and Cornell University. Within three years he was put in charge of diesel engine development.**

**In his rise through the ranks of the organization he played a vital role in the development of two new methods of submarine propulsion, diesel power and atomic energy as applied to the submarine USS *Nautilus* and the *Seawolf which* General Dynamics' Electric Boat Division built.**

**During World War II under his direction the shipyard broke all production records in building 82 submarines. In recognition of this feat Mr. Robinson was awarded a Certificate of Merit by President Harry S. Truman.**

**He was a native of Corning, N.Y. He is survived by his widow, the former Estella Ann Scroggie of New London; a son, Lt. (jg) O. Pomeroy Robinson, III, USN; a daughter, Mrs. Jack B. Joyce, and two sisters, Miss Maude Robinson of New York City and Mrs. J. W. Jones of Corning.**

**Mr. Robinson was a director of the Hartford National Bank and Trust Co., the Seneca Grape Juice Corporation, Dundee, N.Y., the Connecticut Chamber of Commerce, and he was a member of the New England Regional Committee on Atomic Energy.**

**Among the organizations of which he was a member were the Shipbuilders Council of America, the Newcomen Society in North America, the Society of Naval Architects and Marine Engineers, and the American Society of Naval Engineers.**

# HAROLD TRAVIS SMITH

**A friend has passed. The death at the Chelsea Naval Hospital, on 4 May 1956, of Rear Admiral Harold Travis Smith, U. S. Navy, Retired, deprived the Secretary-Treasurer of a very dear friend and the Society of a past Secretary-Treasurer (1929-30) and loyal member of 41 years standing.**

**Travis Smith spent 10 years in general line service after graduating from the Naval Academy in 1909. In 1919 he was designated for "Engineering Duty Only" and spent 27 years, prior to his retirement on 1 November 1946, in demonstrating his proficiency as a naval engineer, his lovability as a human being, his kindness and consideration as a gentleman, and his firmness and fairness as a Naval officer. He had the inherent qualities which gained the respect and friendship of juniors, seniors and associates.**

**As an "Engineering Duty Only" officer prior to World War II he served a tour of duty afloat as Chief Engineer of U.S.S. *Omaha*, and another on the staff of Commander Cruisers, U. S. Fleet. Ashore, he served three tours in the Bureau of Engineering, the last as head of the Design Division (1935-1939), one tour at Portsmouth Navy Yard, and one as head of the Central Drafting Office (Machinery) at New York Navy Yard.**

**He was twice decorated with the Legion of Merit in recognition of World War II service, first as Supervisor of Shipbuilding at Quincy, Massachusetts, for his contribution to the largest shipbuilding program of all time, and then as Fleet Maintenance Officer on the staff of the Commander-in-Chief Pacific Fleet, where his group kept the expanding fleet in operation.**

**From his retirement until his death Admiral Smith lived in Hingham, Massachusetts, where the days were never long enough for him to accomplish those things which he wanted to do.**

**The world has lost a man.**

# CHANGES IN MEMBERSHIP

## ADDITIONS TO MEMBERSHIP

The Society is proud to announce that the following have joined the Society since the publication of the February, 1956, JOURNAL.

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